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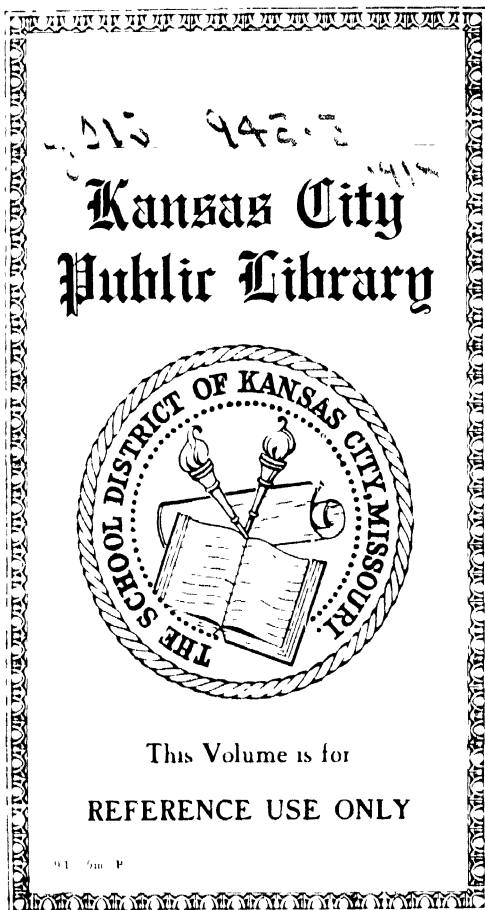
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82nd Year of Issue

The
English Catalogue
of Books
FOR
1918

GIVING IN ONE ALPHABET, UNDER AUTHOR AND TITLE, THE
SIZE, PRICE, MONTH OF PUBLICATION, AND PUBLISHER OF
BOOKS ISSUED IN THE UNITED KINGDOM,
BEING A CONTINUATION OF THE "LONDON" AND "BRITISH" CATALOGUES; WITH THE
PUBLICATIONS OF LEARNED AND OTHER SOCIETIES, AND DIRECTORY OF PUBLISHERS



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London :
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1919

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ANALYSIS OF BOOKS

PUBLISHED DURING 1918 IN THE UNITED KINGDOM.

THE PUBLISHERS' CIRCULAR AND BOOKSELLERS' RECORD records a total of 7,716 books as having been published during the year 1918. This is a decrease of 415 compared with the previous year, but when it is remembered that the period has been one of the utmost difficulty owing to the exhaustion of labour and materials and the enormously increased cost of production in the fourth and fifth years of the War, the total is one which gives striking proof of the vitality and enterprise of British publishing. The decrease is accounted for chiefly by a falling off in the number of works of Fiction (-523) and Juvenile Literature (-155); other classes that have also decreased slightly are Education, Agriculture, Domestic, Business, History, and Geography. On the other hand, Sociology has increased by 112, Technology by 110, Medicine by 80, and Poetry by 98; and there are smaller increases in Religion, Fine Arts, Literature, Military and Naval, and Description.

Viewing the general totals, it will be noted that new publications have increased by 144, while the number of new editions has dropped by 559. An extraordinary proportion of outstanding works have appeared during the year, and the automatic curtailment of production of minor books owing to the scarcity and cost of materials may not have been an unmixed evil from the literary point of view.

The total number of books published in the various classes of literature is a rough indication of the attention bestowed by the public upon them, and it is interesting to compare the order in which the principal classes appear this year and in 1914:—

1914	1918
(1) Fiction	(1) Fiction
(2) Religion	(2) Religion
(3) Science	(3) Sociology
(4) Sociology	(4) Poetry
(5) Technology	(5) History
(6) Poetry	(6) Juvenile
(7) Juvenile	(7) Medicine
(8) Description	(8) Technology
(9) Literature	(9) Military & Naval
(10) History	(10) Science
(11) Medicine	

- | | |
|-----------------------|-----------------|
| (11) Biography | (11) Literature |
| (12) Military & Naval | (12) Biography |

The following totals for the last ten years are also of considerable interest —

Year	New books.	New editions	Total
1909	8,446	2,279	10,725
1910	8,468	2,336	10,804
1911	8,530	2,384	10,914
1912	9,197	2,870	12,067
1913	9,541	2,838	12,379
1914	8,863	2,674	11,537
1915	8,499	2,166	10,665
1916	7,537	1,612	9,149
1917	6,606	1,525	8,131
1918	6,750	966	7,716

It should be noted that in the following table "Education" includes only books about educational theory and practice, and not text books on special subjects, which are classed elsewhere, that under "Music" only works about music are recorded, and that books dealing generally with the European War are classed under "History," while those of a technical nature are placed under the heading "Military and Naval." It would be possible to swell the total to a much greater figure by counting numerous leaflets (Government and other), ephemeral pamphlets, the publications of borough councils and other local government bodies, and musical texts. While it is obvious that our total could be increased greatly by the inclusion of all this literary protozoa, the figures would not represent so accurately the book publishing activity of the United Kingdom.

In these tables each publication is counted as one, whether it is in one or more volumes. Serials that appear later as a collected volume are counted as an ordinary book on the appearance of that volume; so that, for example, the series of "Statutory Rules and Orders" issued by the Government, and amounting to several hundred in the year, are counted as one item on the appearance of the annual collected volume. The same rule applies to volumes of magazines, &c. Further detailed information regarding the year's publishing is supplied by the appended analytical tables.

**CLASSIFIED ANALYSIS OF BOOKS PUBLISHED DURING
THE YEAR 1918**

Classes of Literature.	NEW BOOKS.			NEW EDITIONS	TOTALS FOR 1918	TOTALS FOR 1917
	New Books	Translations	Pamphlets			
Philosophy	167	3	10	26	206	201
Religion	607	8	114	54	783	759
Sociology	447	3	183	29	662	550
Law	110	—	2	18	130	146
Education	148	1	30	8	187	211
Philology	122	—	4	16	142	151
Science	232	5	28	64	329	346
Technology	279	3	9	87	378	268
Medicine, Public Health, &c.	263	11	21	85	380	300
Agriculture, Gardening	153	2	6	21	182	213
Domestic Arts	44	—	—	13	57	93
Business	152	—	5	22	179	217
Fine Arts	122	1	3	12	138	125
Music (Works about)	24	—	2	1	27	46
Games, Sports, &c.	27	—	2	12	41	47
Literature	212	1	4	33	250	216
Poetry and Drama	564	13	15	50	642	544
Fiction	755	22	—	237	1,014	1,537
Juvenile	328	2	4	50	384	539
History	516	11	64	38	629	686
Description and Travel	159	1	6	14	180	167
Geography	47	—	—	21	68	92
Biography	185	3	11	22	221	230
General Works	164	—	—	2	166	134
Military and Naval	261	4	45	31	341	313
Totals	6,088	94	568			
		6,750		968	7,716	8,131
<i>Totals for 1917</i>		<i>6,606</i>		<i>1,525</i>	<i>8,131</i>	

**ANALYTICAL TABLE SHOWING BOOKS PUBLISHED EACH MONTH
DURING 1918.**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Totals 1918	Totals 1917
New	637	391	463	452	478	439	520	421	438	721	630	498	6,088	5,716
Translations	16	11	10	12	9	6	3	5	3	5	10	4	94	108
Pamphlets	57	44	43	56	50	60	54	36	27	63	45	33	568	782
Total New Books	710	446	516	520	537	505	577	462	468	789	685	535	6,750	6,606
New Editions	65	62	102	83	77	69	78	71	93	104	81	81	966	1,525
Totals	775	508	618	603	614	574	655	533	561	893	766	616	7,716	8,131
<i>Total for 1917</i>	<i>606</i>	<i>806</i>	<i>667</i>	<i>591</i>	<i>706</i>	<i>615</i>	<i>667</i>	<i>657</i>	<i>607</i>	<i>705</i>	<i>800</i>	<i>704</i>	<i>8,131</i>	

PREFATORY NOTE

THIS eighty-second yearly issue of **THE ENGLISH CATALOGUE OF BOOKS** comprises the titles (under authors, and subjects or titles) of works published during 1918, and also of some received too late for inclusion in the eighty-first issue.

The main entry for each book begins with the author's surname (if known) in **heavy type**. As an index to these "Author" records, entries are also made under the titles, commencing with their most important words (which usually indicate the *subjects* with which the books deal), or with the first words; the name or word under which the main entry appears is printed in *italics* in these index entries, thus giving a reference to the place where the full information about a book may be found. Main entries and index entries are in one alphabet.

Writers with compound names are entered under the first part of the name, *e.g.* :—

Baring-Gould (Sabine)

and accordingly must be looked for in that order. References are also made, however, from the last part of the name.

The publications of learned Societies are recorded in an Appendix

The names and addresses of the Publishers of Great Britain and Ireland, followed by those of the principal publishers in the United States and Canada, will be found at the end of the volume. The telegraphic and cable addresses and telephone numbers have been added when known.

Following the Preface is an analysis of the books of the year 1918, showing in detail the number of works in each class of literature, and giving the proportions of new books, translations, pamphlets, and new editions

Every effort has been made to obtain the full particulars of the books noted. Special enquiries were made in every case where information was deficient; and most publishers courteously responded. In the cases where entries have been included without prices, the fault lies with the publishers concerned.

Hearty thanks are due to the many publishers, secretaries, librarians, authors and bibliographers who have assisted in making this book more correct and comprehensive than it would have been otherwise

The Editor will be glad to have particulars (author, title, size, price, publisher and month of publication) of any work which may have been omitted. Information regarding each book should be given on a separate slip of paper or postcard. It should be addressed to *The Editor of THE ENGLISH CATALOGUE OF BOOKS* "Publishers' Circular" Office, 19, Adam Street, Strand, London, W.C. 2.

THE EDITOR.

THE ENGLISH CATALOGUE

1918

*. The names or words printed in *Italic* in the Index Entries are those under which the books will be found fully described in the main entries.

*. In addition to the names of book-sizes, such as cr. 8vo., royal 8vo., &c., the sizes are also given whenever possible in inches, 1 inch = 2½ centimetres.

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- Geological Society**, Burlington House, W. 1
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- Geological Survey and Museum**, 28, Jermyn Street, S.W. 1 A. Strahan, *Director*
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- Hull Scientific and Field Naturalists' Club**. T. Stamford, *Hon Sec*, Municipal Museum, Hull
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- Imperial Institute of the United Kingdom**, the Colonies and India, South Kensington, London, S.W. 7 Prof. Wyndham R. Dunstan, *Director*
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- Industrial Law Committee**, 34, Mecklenburgh Square, London, W.C. 1
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Transactions.

APPENDIX

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Mineralogical Magazine. Vol 18, no 85, Aug '18, 5s

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APPENDIX

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Scottish Text Society, 11, Hill Street, Edinburgh. W. Traquair Dickson, Hon. Sec

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Professional notes

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APPENDIX

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Zoological Record, Vol. 53 (1916) No. 9, Arthropoda (General), by Dr D. Sharp, 1s 6d; No. 17, Aves, by W. I. Slater, 6s

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- CLEGG (W. E.), 30 Market Place and Peter Street,
Oldham.
- CLERKENWELL PRESS, LTD., 76 & 78 Clerkenwell
Road, E.C. 1.
- CLIFTON PUBLISHING HOUSE, 20 Clifton Street,
Finsbury, E.C. 2.
- CLIVE (W. B.)—See University Tutorial Press, Ltd.
- CLOWES (WILLIAM) & SONS, LTD., 31, Haymarket,
S.W. 1. [Clowes, London; 2822 Regent.]
- COBDEN-SANDERSON (T. J.)—See Doves Press.
- COLLIERY GUARDIAN Co., LTD. (Chichester
Press), 30 & 31 Fumival Street, Holborn,
E.C. 4. [Colliery Guardian, Fleet; 1354 Hol-
born.]
- COLLINGRIDGE (W. H. & L.), 148 & 149 Aldersgate
Street, E.C. 1. [Collingridges, Cent; 148 and
1086 City.]
- COLLINGWOOD (BROS.), 329, High Holborn, W.C. 1.
- COLLINS (WILLIAM), SONS & Co., LTD., 4 & 5 Bride-
well Place, New Bridge Street, E.C. 4; 48 Pall
Mall, S.W. 1; and at 144 Cathedral Street,
Glasgow. [Collins, Ltd., Fleet, London; 7170
City; 788 Gerrard.]
- COLNAGHI (P. & D.) & OBACH, 144, 145 & 146 New
Bond Street, W. 1. [Colnaghi, Wesdo, London;
6356 Mayfair.]
- COLOUR, LTD., 53 Victoria Street, S.W. 1. [6385
Victoria]
- COLOUR SERVICE Co., 19 Cannon Street, Manchester.
- COLSTON PUBLISHING Co., LTD., 4 Colston Street,
Bristol.
- COMBRIDGE (A. J.) & Co., 30 & 31 Newgate Street, E.C. 1.
- COMBRIDGE (C.), 3-5 New Street, 142 Broad Street,
and 9 Bull Ring, Birmingham.
- COMBRIDGE'S LIBRARY (S. COMBRIDGE & C. F. COOK),
56 & 70 Church Road, Hove. [P.O. 156Y,
Hove 2009X.]
- COMMIN (J. G.), 230 High Street, Exeter. [Commin,
Bookseller, Exeter.]
- COMPENDIUM PUBLISHING Co., 93 and 94 Chancery
Lane, W.C. 2. [1768 Holborn.]
- COMTELBORO, LTD., 11, Tokenhouse Yard, E.C. 2.
[Comtelburo, Stock; 22 Central, 1827 London
Wall.]
- CONGREGATIONAL UNION OF ENGLAND AND WALES
(INCORPORATED) PUBLICATION DEPARTMENT,
1 & 2 Congregational Memorial Hall, 15 Farring-
don Street, E.C. 4; 4 Fleet Lane, E.C. 4.
[Memorial, Cent.]
- "CONNOSSUD," 1 Duke Street, St. James's, S.W. 1.
[Novedad, St. James's; 7995 Gerrard.]
- CONSTABLE & Co., LTD., 10 and 12 Orange Street,
Leicester Square, W.C. 2. [Diagoba, West-
rand; 2432 Regent.]
- CONSTABLE (T. & A.), University Press, 11, 13 & 15
Thistle Street, Edinburgh. [Constable, Edin-
burgh; 85 Central.]

- COOK (THOMAS) & SON, Ludgate Circus, E.C. 4 [Coupon; 3160 Holborn.]
- CO-OPERATIVE UNION, LTD., Holyoake House, Hanover St., Manchester. [Congress; 1504 City.]
- CO-PARTNERSHIP PUBLISHERS, LTD., 6, Bloomsbury Square, W.C. 1.
- COPE & FENWICK, 8, Buckingham Street, Strand, W.C. 2
- CORNISH BROS., LTD., 39 New Street, Birmingham.
- CORNISH (J. E.), LTD., 16 St. Ann's Square, Manchester.
- CORNISH (JAMES) & SONS, 37 Lord Street and 42 North John Street, Liverpool. [4951 Bank.]
- COUNCIL FOR THE STUDY OF INTERNATIONAL RELATIONS, 11 Adelphi Terrace, Strand, W.C. 2
- COUNTRY GENTLEMEN'S ASSOCIATION, LTD., 33 Henrietta Street, W.C. 2 [Ruralness, Rand; 2602 Regent.]
- "COUNTRY LIFE," 17-21 Tavistock Street, Covent Garden, W.C. 2. [Country Life; 2748 Gerrard.]
- COX (HORACE), LTD, Windsor House, 15-25 Bream's Buildings, Chancery Lane, E.C. 4. [Field Newspaper, London; 218, &c Holborn.]
- CRAIGWOOD HOUSE PUBLISHING CO., Cupar-Pife
- CRANE, CRANE & CO., 17 Farringdon Street, E.C. 4
- CRISP (F. A.)—See Grove Park Press.
- CRYSTAL PRESS, LTD., 36-39 Maiden Lane, W.C. 2, 91 Regent Street, W. 1.
- CUALA PRESS, Churchtown, Dundrum, Ireland.
- CURRIE (JOHN), 3 Marleston Crescent, Edinburgh.
- CURSITOR PUBLISHING CO., 12 Curzor Street, E.C. 4. [Spellable, Fleet; 2996 Holborn.]
- CURTIS (A. C.), LTD., High Street, Guildford, and at Godalming.
- CURTIS & BEAMISH, LTD., 50, Hertford Street, Coventry.
- CURTIS & DAVISON, 7A Church Street, Kensington, W. 8.
- CURWEN (JOHN) & SONS, LTD., 24 Berners Street, W. 1 [Curwen, Phone; 9410 Gerrard.]
- DAIRY WORLD, 98 & 99 Fetter Lane, E.C. 4.
- DAISY BANK PUBLISHING CO., (late) 107 and 109 Wellington Street, Gorton, Manchester.
- DANGERFIELD PRINTING CO., LTD., 23 Bedford Street, Strand, W.C. 2. [Dangerfield, Westrand; 1911 Regent.]
- DANIEL (C. W.), LTD., 3 Tudor Street, E.C. 4. [Oprodan, Fleet; 7611 Central.]
- DARLINGTON & CO., Greenheys, Llangollen, North Wales. [Darlington, Llangollen; 9.]
- DAVIS (JOHN), Successor to Thomas Laurie, Free Age Press, 13 Paternoster Row, E.C. 4.
- DAVIS (R.), 30 Leadhall Lane, Harrogate.
- DAVIS & MOUGHTON, LTD., 2 Ludgate Hill, Birmingham.
- DAVY (JOHN) & SONS, 8 and 9 Frith Street, W. 1. [3704 Gerrard.]
- DAWBARN & WARD, LTD., c.o. Routledge (G.) & Sons, Ltd., 68-74 Carter Lane, E.C. 4
- DAWSON (WILLIAM) & SONS, LTD., Cannon House, Bream's Buildings, E.C. 4. [Nonnac, Fleet; 426 Holborn; Dawlex, Fleet; 121 Cannon Street, E.C. 4; 17 Craven Street, W.C. 2.
- DAY (ERNEST J.), & Co, 6 Gerrard Street, W. 1. [3656 Gerrard.]
- DEAN & SON, LTD., 160A Fleet Street, E.C. 4, and 18-19 Johnson's Court, Gough Square, E.C. 4 [Debrett, Fleet; 119 Holborn.]
- DEANE (H. F. W.) & SONS, The Year Book Press, Ltd, 31 Museum Street, W.C. 1. [3183 Museum.]
- DEAN'S RAG BOOK CO., LTD., 2-14 Newington Butts, S.E. 1 [Outwitting, Sedist; 2076 Hop.]
- DEIGHTON, BELL & CO., LTD, 13 Trinity Street, Cambridge [239.]
- DE LA MORE PRESS—See Moring (A.), Ltd.
- DE LA RUE (T.) & CO., LTD., 108-117 Bunhill Row, E.C. 1. [Delarue, Finsquare; 4227 London Wall.]
- DENNY (A. & F.), 147 Strand, W.C. 2. [5254 Central.]
- DENT (J. M.) & SONS, LTD., 10-13 Bedford Street, W.C. 2. [Templarlan, London; 3052 Regent.]
- DIEMER (F.), FINCK & BAYLAENDER, Succ., Cairo, P.O.B. 311.
- DIGBY, LONG & CO., 16A Bouverie Street, Fleet Street, E.C. 4
- DIRECTORY PUBLISHING CO., LTD., 15 Farringdon Avenue, E.C. 4.
- DOBELL (P. J. AND A. E.), 54 and 77 Charing Cross Road, W.C. 2 [Biblia, Westrand; 4197 Gerrard.]
- DOBSON (C. M.), 146 Kensington High Street, W. 8.
- DOIG BROS. & CO., LTD., 54 Stowell Street, Newcastle-on-Tyne
- DOUGLAS (DAVID), 9 Castle Street, Edinburgh.
- DOUGLAS & FOULIS, 9 Castle Street, Edinburgh.
- DOVES PRESS (T. J. CORDEN-SANDERSON), 15 Upper Mall, Hammersmith, W. 6.
- DOW & LESTER, Foresters' Hall Place, Clerkenwell Road, E.C. 1 [430 Holborn.]
- DOWNIE (T. FRENCH), 21, Warwick Lane, E.C. 4
- DRAKE, DRIVER & LEAVER, LTD, 20, 22 and 24, Rosebery Avenue, E.C. 1 [Drakes, Holb.; 2781 Holborn.]
- DRANE'S, LTD, 13 Harp Alley, Farringdon Street, E.C. 4. [6017 City.]
- DRUMMOND'S TRACT DEPOT, 17 Dumbarton Road, Stirling, N.B. [Tract Depot, Stirling; 84.]
- DRYDEN PRESS. See John Davy & Sons.
- DRYDEN PUBLISHING CO., LTD, Central House, 34-36 Oxford Street, W. 1
- DUCKWORTH & CO., 3 Henrietta Street, Covent Garden, W.C. 2 [Ductarius, Rand, London; 367 Gerrard.]
- DUFFY (JAS.) & CO., LTD, 38 Westmoreland Street, Dublin.
- DULAU & CO., LTD, 34-36 Margaret Street, W. 1.
- DUNDALGAN PRESS, Dundalk.
- DUTTON'S NATIONAL BUSINESS COLLEGE, 92 and 93 Great Russell Street, W.C. 1.
- DUTY AND DISCIPLINE MOVEMENT, 117 Victoria Street, S.W. 1. [5661 Victoria.]
- DWELLY (E.), King's Road, Fleet, Hants.
- EARLY ENGLISH TEXT SOCIETY—See Paul (Kegan), Trench, Trubner & Co.
- EAST AND WEST, LTD., 3 Victoria Street, S.W. 1. [1201 Victoria.]
- EASTERN PAPERS, LTD, 79 Gracechurch Street, E.C. 3. [6156 Avenue.]
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- ECONOMICS AIRCRAFTS, LTD, 32 Charing Cross, S.W. 1.
- "ECONOMIST," Granville House, Alundel Street, Strand, W.C. 2. [2110 Gerrard.]
- EDUCATIONAL BOOK CO., LTD., 17 New Bridge Street, E.C. 4 [Educatrice, Fleet; 1 Central.]
- EDUCATIONAL CO. OF IRELAND, LTD., 89 Talbot Street, Dublin.
- EDUCATIONAL PUBLISHING CO., LTD., Trade Street, Cardiff.
- EDUCATIONAL SUPPLY ASSOCIATION, LTD., 40-44 Holborn Viaduct, E.C. 1 [Educational, Cent; 3480 Central.]
- EDWARDS & BRYNING, LTD., (incorporating J. Clegg, Ltd.), Rochdale.
- EDWARDS (FRANCIS), 83A High Street, Marylebone, W. 1. [Finality, Baker; 803 Mayfair.]
- EDWARDS (G.) & CO, 28 Warner Street, E.C. 1.
- EFFICIENCY MAGAZINE, 3 and 4 Lincoln's Inn Fields, W.C. 2. [Sheltific, Holb.; 5102 Holborn.]
- EGOIST, THE, LTD, 23 Adelphi Terrace House, 1-3 Robert Street, W.C. 2.
- ELECTRICAL PRESS, LTD., 13-16, Fisher Street, Holborn, W.C. 1. [Faisighted, Westcent; 2012 Holborn.]
- ELECTRICIAN PRINTING & PUBLISHING CO., LTD. See Benn Bros., Ltd
- ELLIOT (ANDREW), 17 Princes Street, Edinburgh.
- ELSINORE PUBLISHING CO., 98, South Hill Park, Hampstead, N.W. 3.
- ELYSIAN PUBLISHING SOCIETY, (late) 79 Reginald Terrace, Leeds.
- EMMOTT & CO., LTD., 20 Bedford Street, Strand, W.C. 2. [3529 Gerrard.]
- "EMPIRE, THE," 61, Fleet Street, E.C. 4.
- EMPIRE PARLIAMENTARY ASSOCIATION, 64 Victoria Street, S.W. 1. [Emparlasso, Sowest; 5814 Victoria.]
- ENCYCLOPEDIA PRESS, INC., 119 High Holborn, W.C. 1 [Cyclopress; 5281 Holborn.]
- ENGINEERING, 35 & 36 Bedford Street, Strand, W.C. 2. [Engineering, Westrand; 3663 and 8508 Gerrard.]
- ENGLISH ASSOCIATION, Imperial College Union, Prince Consort Road, S.W. 7.

- ENGLISH CHURCH UNION, 31 Russell Square, W.C. 1 [Communicants, Westcent; 1243 Museum.]
- "ENGLISH" PUBLISHING Co., 123 Charing Cross Road, W.C. 2
- ENGLISH ZIONIST FEDERATION, 69, Leadenhall Street, E.C. 3. [5617 Avenue.]
- ENOCH & SONS, 58, Great Marlborough Street, W. 1 [Litoff, Reg; 5595 Gerrard.]
- EPWORTH PRESS, 25-35 City Road, E.C. 1 [Book Room, Finsquare; 1770 London Wall] 26 Paternoster Row, E.C. 4. 126 and 128 Horseferry Road, S.W. 1. [5430 Victoria.]
- "ERA," 35, Wellington Street, W.C. 2. [The Era; 4747, 1433 Central.]
- ESSEX HOUSE PRESS, 17, Cheyne Walk, Chelsea, S.W. 3
- ESTATES GAZETTE, LTD., 33-35 Kirby Street, Hatton Garden, E.C. 1 [198 Holborn; 10474 Central.]
- EUGENE & Co., 17, Park Avenue, Willesden Green, N.W. 2
- EUGENICS EDUCATION SOCIETY, 11 Lincoln's Inn Fields, W.C. 2 [5797 Holborn]
- EUSTON PRESS, 6 and 8 Euston Buildings, N.W. 1.
- EVANS BROS., LTD., Montague House, Montague Street, Russell Square, W.C. 1 [Byronic, Westcent; 2230 Museum]
- EVANS (THOMAS), Park Road, Redditch.
- EVERETT & Co., LTD., 42 Essex Street, Strand, W.C. 2. [Accounted, Strand; 396 City.]
- EWART, SEYMOUR & Co., LTD., 231 and 232 Strand, W.C. 2. [Ewsemo, Strand; 3912 Central]
- EYRE & SPOTTISWOODE, LTD., East Harding Street, E.C. 1, 2 Victoria Street, Westminster, S.W. 1; 33 Paternoster Row; 12 & 13 Paternoster Square, E.C. 4. [Eyre, Fleet; 2200 Holborn, 1460 Victoria; Exalted, Cent; 5166 City.]
- FABIAN SOCIETY, 25 Tothill St., S.W. 1 [1915 Victoria.]
- FAIRGRIEVE (J. B.), 7 and 9 Cockburn St., Edinburgh.
- FAITH PRESS, LTD., 22 Buckingham Street, Strand, W.C. 2. [2882 Regent.]
- FALLON BROS., LTD., 13 and 14, Dame Court, Dublin [Scholastic, Dublin; 4803]
- FAMILY HERALD PRESS (WILLIAM STEVENS, LTD.), 23-24 Henrietta Street, Covent Garden, W.C. 2 [3214 Gerrard]
- FARNCOMBE (C. J.) & SONS, LTD., 30 Imperial Buildings, New Bridge Street, E.C. 4 [8366 Central]
- FASHION JOURNALS GUILD, 14 Woodstock Street, W. 1.
- FAWCETT & Co., 125, Strand, W.C. 2
- "FEATHERED WORLD," 9 Arundel Street, Strand, W.C. 2. [Feathered World]
- FIELD AND QUEEN—See COX (Horace).
- FIFIELD (A. C.), 13 Clifford's Inn, E.C. 4 [8295 City.]
- FINANCIAL NEWS, LTD., 111 Queen Victoria Street, E.C. 4. [Finews, Cent.; 6830 City]
- FINANCIAL REVIEW OF REVIEWS, 6 Grafton Street, New Bond Street, W. 1
- FINANCIAL TIMES, LTD., 72 Coleman Street, E.C. [Finantimo, Ave; 3436 London Wall]
- FINANCIER AND BULLIONIST, LTD., 49-57 Wool Exchange, Coleman Street, E.C. 2 [Finanzmann, Ave; 8148 London Wall]
- FINCK & BAYLAENDER—See DIEMER (F.).
- FINE ART SOCIETY, LTD., 148 New Bond Street, W. 1 [Finart; 3767 Gerrard.]
- FINE ART TRADE JOURNAL, 13 Buckingham Street, Strand, W.C. 2
- FISHER (EDEN) & Co., LTD., 6, 7, 8 Clement's Lane, Lombard Street, E.C. 4; 95, 96 & 97 Fenchurch Street, E.C. 3 [Composed; 5787, 3717 Avenue.]
- FISHING GAZETTE, LTD., 19 Adam Street, W.C. 2 [1196 Gerrard]
- FLEET (THE), LTD., 11 Henrietta Street, W.C. 2
- FOOD & COOKERY PUBLISHING AGENCY, 329 Vauxhall Bridge Road, S.W. 1 [217 Victoria]
- FOREIGN & COLONIAL COMPILING & PUBLISHING Co., 56 Ludgate Hill, E.C. 4.
- FORES (G. P.), 41, Piccadilly, W. 1. [3549 Mayfair]
- FOULIS (T. N.), 15 Frederick Street, Edinburgh; 91 Great Russell Street W.C. 1. [1991 Museum.]
- FOULSHAM (W.) & Co., LTD., 61 Fleet Street, E.C. 4. [7166 City.]
- FOUNTAIN PUBLISHING Co. (SIVORI LEVEY PRODUCTIONS), 6 Rochampton Lane, S.W. 15.
- FOWLER (L. N.) & Co., 7 Imperial Arcade, Ludgate Hill, E.C. 4 [Phrenologist, London; 2235 Holborn.]
- FOYLE (W & G.), 121 and 123 Charing Cross Road, W.C. 2 [Foylibra; 8180 Gerrard]
- FRASER, ASHER & Co., LTD., 73 Dunlop Street, Glasgow.
- FRENCH (SAMUEL), LTD., 26 Southampton Street, Strand, W.C. 2 [2238 Gerrard.]
- FROWDE (HENRY) AND HODDER & STOUGHTON, Oxford Press Warehouse, Falcon Square, E.C. 1 [Oxymoron, Cent; 8961 City.]
- FROWDE (H.)—See also Milford (Humphrey)
- FULTON-MANDERS PUBLISHING Co., Brownlow House, 50 and 51, High Holborn, W.C. 1 [Malterm, Holb; 491 Holborn]
- FUNK & WAGNALLS Co., 134 Salisbury Square, E.C. 4 [Funknalls, Fleet; 5909 City]
- FURNIVAL PRESS, 23-25, Furnival Street, E.C. 4.
- GALE & POLDEN, LTD., 2 Amen Corner, Paternoster Row, E.C. 4, and Wellington Works, Aldershot [Picquets, Phone, London; 397 Central]
- GALL & INGLIS, 20 Bernard Terrace, Edinburgh; 31 Henrietta Street, Covent Garden, W.C. 2 [Gall, Edinburgh; 6151 Edinburgh]
- GALLOWAY (SYDNEY V.), 21 Pier Street, Aberystwyth
- GALLOWAY & PORTER, 30 Sidney Street, Cambridge
- GAMAGE (A. W.) LTD., Holborn, E.C. 1. [2700 Holborn.]
- GANES, LTD., 85 Shaftesbury Avenue, W. 1. [Gainsaid, Piccy; 8853 Gerrard]
- GARDEN CITY PRESS, LTD., Letchworth, Herts.
- "GARDEN LIFE," 51 Great Queen Street, W.C. 2
- GARDENING ILLUSTRATED, 63 Lincoln's Inn Fields, W.C. 2 [731 Holborn]
- GARDNER (A. M.) & Co., LTD., 108 Shoe Lane, E.C. 4 [Disallowed, Fleet; 5495 Holborn.]
- GARDNER (ALEXANDER), 7 Gilmour Street, Paisley. [Nat. 411.]
- GARDNER (WELLS), DARTON & Co., LTD., 3 & 4 Paternoster Buildings, E.C. 4, and 44 Victoria Street, S.W. 1 [Publishers, London; 2713 Central and 2911 Victoria.]
- "GAS WORLD," 8 Bouverie Street, E.C. 4 [Allanias, Fleet; 9852 City]
- GAY & HANCOCK, LTD., 21 Bedford Row, W.C. 1. [345 Holb]
- GEE & Co., LTD., 34 Moorgate Street, E.C. 2 [7321 Central.]
- GENERATION PRESS, 138 Fleet Street, E.C. 4.
- GEOGRAPHIA, LTD., 55 Fleet Street, E.C. 4. [Geografo; 4965 City]
- GEOGRAPHICAL PUBLISHING Co. See British Geographical Publishing Co.
- GEORGE (R.) & SONS, LTD., 23 Jacob Street, Dockhead, S.E. 1. [Georgetta; 1842 Hop]
- GERRARDS, LTD.—See Westminster Press
- GIBBINGS & Co., 18 Bury Street, W.C. 1
- GIBBONS (STANLEY), LTD., 391 Strand, W.C. 2 [Philatelic, Rand; 9031 Gerrard]
- GIBSON (JOHN), 63 Coleman Street, E.C. 2 [5690 London Wall]
- GIBSON (R.) & SONS (GLASGOW) LTD., 45 Queen Street, Glasgow.
- GIEVES PUBLISHING Co., LTD., 2 The Hard, Portsmouth
- GILBERT-WOOD (C.), Norfolk House, Norfolk Street, Strand, W.C. 2 [Gilbeewood; 4680 Gerrard]
- GILL (C.) & SONS, LTD., 13 Warwick Lane, E.C. 4. [Gill & Sons, London; 1711 Central]
- GILL (L. UPCOTT) & SON, LTD., Bazaar Buildings, 55-57 Drury Lane, W.C. 2 [Upcott; 1046 Gerrard]
- GILL (M. H.) & SON, LTD., 50, Upper O'Connell Street, Dublin [Gill, Dublin; 365]
- GINN & Co., 9 St. Martin's Street, Leicester Square, W.C. 2 [Pedagogy, Westrand; 6192 Gerrard.]
- GIRL'S OWN PAPER, 4 Bouverie Street, E.C. 4
- GLAISHER (HENRY J.), 55 and 57 Wigmore Street, W. 1. [74 Mayfair.]

- GLASS (W.) & Co.**, (late) Lincoln House, High Holborn, W.C. 1.
- GLEDSDALE & JENNINGS, LTD.**, 29 and 31 North John Street and 27 King Street, Liverpool.
- GLOBE ENCYCLOPEDIA Co.**, 30 Fleet Street, E.C. 4.
- GLOVER (H. W.)**, 114 Leadenhall Street, E.C. 3. [12645 Central]
- GOODALL (CHARLES) & SON, LTD.**, 24 Great College Street, N.W. 1 [Aldine]
- GOOSE & SON, LTD.**, 2 Haymarket, and 19 Rampant Horse Street, Norwich.
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- GOTHIC PRESS**, 106, Peckham Rye, S.E. 15
- GOUPIL & Co (MANZI, JOYANT & Co.)**, 26 Henrietta Street, Covent Garden, W.C. 2 [Goupille, London; 2877 Gerrard]
- GOWANS & GRAY, LTD.**, 58 Cadogan Street, Glasgow, and 5 Robert Street, Adelphi, W.C. 2
- GRAFTON & Co.**, 8 Coptic Street, Bloomsbury, W.C. 1 [1984 Museum.]
- GRAHAM & LATHAM, LTD.**, 27 and 28 Old Jewry, E.C. 2 [4139 City.]
- GRANT EDUCATIONAL Co., LTD.**, 91 and 93 Union Street, Glasgow.
- GRANT (JOHN)** (Robert Grant and John Grant, jun.), 31 and 34 George IV Bridge, Edinburgh [Books, Edinburgh; 836]
- GRANT (R.) & SON**, 107 Princes Street, Edinburgh. [Giles, Edinburgh; 1919.]
- GRATTAN (H. H. G.)**, 17 Borough High Street, London Bridge, S.E. 1
- GRAY'S RAILWAY PUBLISHING Co., LTD.**, 4 St. Ann's Square, Manchester.
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- GREENWOOD (H.V.) & Co., LTD.**, 24 Wellington Street, Strand, W.C. 2 [2722 Gerrard.]
- GREGORY (GEORGE)**, 5 Argyle Street, Bath
- GRESHAM PRESS**—See Unwin Bros.
- GRESHAM PUBLISHING Co., LTD.**, 66, Chandos Street, W.C. 2 [Literato, Westrand, 45 Gerrard]
- GREVILL (H.) & Co. (late)**, 33 King Street, Covent Garden, W.C.
- GRIFFIN (CHARLES) & Co., LTD.**, 12 Exeter Street, Strand, W.C. 2 [Explanatus, Rand, 3634 Gerrard.]
- GRIFFIN (J.) & Co**—See Gieves Publ. Co., Ltd
- GRIFFITHS (FRANCIS)**, 34 Maiden Lane, Strand, W.C. 2 [1449 Gerrard.]
- GROOM (FORSTER) & Co., LTD.**, 15 Charing Cross, S.W. 1. [9280 Central]
- GROVE PARK PRESS**, 270 Walworth Road, S.E. 17 [Crisp, London]
- GURNEY & JACKSON**, 33 Paternoster Row, E.C. 4 [1665 City.]
- GYPSY PRESS**, (late) 8 and 9 St. James' Market, S.W. 1; 20 Upper Liffey Street, Dublin
- H.M. STATIONERY OFFICE**—See Stationery Office
- HACHETTE & Co.**, 18 King William Street, Charing Cross, W.C. 2 [Hacheco; 9467 Central.]
- HADDEN, BEST & Co.**, 5 West Harding Street, E.C. 4; and 26 Fetter Lane, E.C. 4 [Hadden Best, London; 2204 Central.]
- HALL (H.V. J.) & Co.**, 25 S. Molton Street, W. 1. [4087 Mayfair]
- HALL (J.) & SON**, 51 Trumpington Street, Cambridge.
- HAMMOND (J. G.) & Co., LTD.**, 32-36 Fleet Lane, E.C. 4 [6661 City.]
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- HAMMOND, HAMMOND & Co., LTD.**, Wardrobe Chambers, Queen Victoria Street, E.C. 4
- HAMPSHIRE HOUSE WORKSHOPS.**—See Pepler (Douglas)
- HAND & Co.**, 94 Paddington, Liverpool
- HANNA (FREDERICK)**, 29 Nassau Street, Dublin.
- HARDING & MORE, LTD.**, 119, High Holborn, W.C. 1.
- HARDWICK (WILLIAM)**—See Gothic Press.
- HARPER & BROTHERS**, 45 Albemarle Street, W. 1. [Tele., Harpspel, London; Cable, Harpsam, London; 85 Regent.]
- HARRAP (GEO. G.) & Co., LTD.**, 2 and 3 Portsmouth Street, Kingsway, W.C. 2. [Butiboox, Estrand; Cable, Harrap, London; 1110 Holborn.]
- HARRISON & SONS**, 45 Pall Mall, S.W. 1; 45-47 St. Martin's Lane, W.C. 2. [1411 Regent. Reginarum, Westrand; 5412 Regent]
- HAYES (ROBERT), LTD.**, 61, Fleet Street, E.C. 4
- HAYMAN, CHRISTY & LILLY, LTD.**, 113, 115 & 117 Farringdon Road, E.C. 1
- HAZELL, WATSON & VINEY, LTD.**, 52 Long Acre, W.C. 2 [Plaintiff, Phone, 605 Gerrard]
- HEADLEY BROTHERS, PUBLISHERS, LTD.**, Commerce House, 72, Oxford Street, W. 1 [Swarthmore, Ox, 2123 Museum]
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- HEALTH & VIM, LTD**—See Health Promotion, Ltd
- HEALTH PROMOTION, LTD**, 19 Ludgate Hill, E.C. 4 [9694 City.]
- HEATH (D. C.)**—See Harrap (G. G.) & Co., Ltd
- HEATH, CRANTON, LTD.**, 6 Fleet Lane, Farringdon Street, E.C. 4 [6081 City]
- HEFFER (W.) & SONS, LTD.**, 4 Petty Cury, Cambridge. [Heffer, Cambridge; 862 Cambridge]
- HEINEMANN (WILLIAM)**, 20 and 21 Bedford Street, Strand, W.C. 2 [Sunlocks, Westrand; 5675 Gerrard.]
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- NORTHERN PUBLISHING CO, 5 Eilswick Court, Newcastle-upon-Tyne.
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- P. P. PRESS, King Edward Street, Liverpool. [Almanac; 6303 Cent.]
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12. $9x^2 + 16y^2 = 144$.

Ans. 48π .

13. $y = xe^x$, $y = 0$, $x = 1$.

$\frac{1}{4}\pi(e^2 - 1)$.

14. The witch $(x^2 + 4a^2)y = 8a^3$, $y = 0$.

$4\pi^2 a^3$.

15. $\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^{\frac{2}{3}} = 1$.

$\frac{8}{3}\pi ab^2$.

16. $y^2(2a - x) = x^3$, $y = 0$, $x = a$.

$0.2115\pi a^3$.

17. $y = x^2 - 6x$, $y = 0$.

18. $y^2 = (2 - x)^3$, $y = 0$, $x = 0$, $x = 1$.

19. $y^2(4 + x^2) = 1$, $y = 0$, $x = 0$, $x = \infty$.

20. $(x - 1)y = 2$, $y = 0$, $x = 2$, $x = 5$.

Find the volume generated by revolving about OY the areas bounded by the following loci.

21. $y = x^3$, $y = 0$, $x = 2$.

Ans. $\frac{64}{5}\pi$.

22. $2y^2 = x^3$, $y = 0$, $x = 2$.

$\frac{32}{7}\pi$.

23. $y = e^x$, $y = 0$, $x = 0$.

2π .

24. $9x^2 + 16y^2 = 144$.

64π .

25. $\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^{\frac{2}{3}} = 1$.

$\frac{4}{5}\pi a^2 b$.

26. $y^2 = 9 - x$, $x = 0$.

27. $x^2 = 16 - y$, $y = 0$.

28. $y^2 = ax$, $y = 0$, $x = a$.

29. The equation of the curve OA in the figure is $y^2 = x^3$. Find the volume generated when the area

(a) OAB is revolved about OX .

Ans. 64π .

(b) OAB is revolved about AB .

$\frac{1024}{3}\pi$.

(c) OAB is revolved about CA .

$\frac{704}{5}\pi$.

(d) OAB is revolved about OY .

$\frac{512}{7}\pi$.

(e) OAC is revolved about OY .

$\frac{384}{7}\pi$.

(f) OAC is revolved about CA .

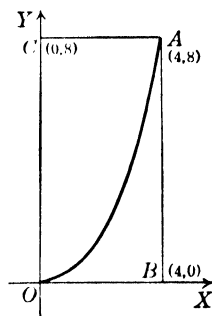
$\frac{576}{5}\pi$.

(g) OAC is revolved about AB .

$\frac{3136}{3}\pi$.

(h) OAC is revolved about OX .

192π .



30. Find the volume of the oblate spheroid generated by revolving the area bounded by the ellipse $b^2x^2 + a^2y^2 = a^2b^2$ about the y -axis.

Ans. $\frac{4}{3}\pi a^2 b$.

31. A segment of one base of thickness h is cut from a sphere of radius r . Show by integration that its volume is $\frac{\pi h^2(3r - h)}{3}$.

Calculate the volume generated by revolving about each of the following lines the area which it cuts from the corresponding curve.

32. $y = 3$; $y = 4x - x^2$. *Ans.* $\frac{16}{15} \pi$.
 33. $x = 4$; $y^2 = x^3$. $\frac{20}{3} \frac{1}{5} \pi$.
 34. $y = -4$; $y = 4 + 6x - 2x^2$. $\frac{12}{3} \frac{5}{3} \pi$.
 35. $y = x$; $y = x^2$. $\frac{1}{60} \pi \sqrt{2}$.
 36. $y = x$; $y = 4x - x^2$. $\frac{5}{20} \pi \sqrt{2}$.
 37. $y = x + 7$; $y = 9 - x^2$. $\frac{5}{20} \pi \sqrt{2}$.
 38. $x + y = 1$; $\sqrt{x} + \sqrt{y} = 1$. $\frac{1}{15} \pi \sqrt{2}$.
 39. $x + y = 7$; $xy = 6$.

40. Find the volume generated by revolving one arch of the cycloid

$$x = r \text{ arc vers } \frac{y}{r} - \sqrt{2ry - y^2}$$

about OX , its base.

HINT. Substitute $dx = \frac{y dy}{\sqrt{2ry - y^2}}$, and limits $y = 0$, $y = 2r$, in (E), Art. 160. *Ans.* $5\pi^2 r^3$.

41. Find the volume generated by revolving the catenary $y = \frac{a}{2} \left(e^{\frac{x}{a}} + e^{-\frac{x}{a}} \right)$ about the x -axis from $x = 0$ to $x = b$.

$$\text{Ans. } \frac{\pi a^3}{8} \left(e^{\frac{2b}{a}} - e^{-\frac{2b}{a}} \right) + \frac{\pi a^2 b}{2}.$$

42. Find the volume of the solid generated by revolving the cissoid $y^2 = \frac{x^3}{2a - x}$ about its asymptote $x = 2a$. *Ans.* $2\pi^2 a^3$.

43. Given the slope of the tangent to the tractrix $\frac{dy}{dx} = -\frac{y}{\sqrt{a^2 - y^2}}$, find the volume of the solid generated by revolving it about OX . *Ans.* $\frac{2}{3} \pi a^3$.

44. Show that the volume of a conical cap of height a cut from the solid generated by revolving the rectangular hyperbola $x^2 - y^2 = a^2$ about OX equals the volume of a sphere of radius a .

45. Using the parametric equations of the hypocycloid

$$\begin{cases} x = a \cos^3 \theta, \\ y = a \sin^3 \theta, \end{cases}$$

find the volume of the solid generated by revolving it about OX .

$$\text{Ans. } \frac{32}{105} \pi a^3.$$

46. Find the volume generated by revolving one arch of the cycloid

$$\begin{cases} x = a(\theta - \sin \theta), \\ y = a(1 - \cos \theta) \end{cases}$$

about its base OX .

$$\text{Ans. } 5\pi^2 a^3.$$

Show that if the arch be revolved about OY , the volume generated is $6\pi^3 a^3$.

47. Find the volume generated if the area bounded by the curve $y = \sec \frac{1}{2} \pi x$, the x -axis, and the lines $x = \pm \frac{1}{2}$ is revolved about the x -axis.

Ans. 4.

48. The area under the curve $y = e^x \sin x$ from $x = 0$ to $x = \pi$ is revolved about the x -axis. Find the volume generated.

49. Given the curve $x = t^2$, $y = 4t - t^3$. Find (a) the area of the loop and (b) the volume generated by the area inside the loop when revolved about the x -axis.

Ans. (a) $\frac{256}{5}$; (b) 67.02.

50. Revolve the area bounded by the two parabolas $y^2 = 4x$ and $y^2 = 5 - x$ about each axis and calculate the respective volumes.

Ans. OX : 10π ; OY : $\frac{128}{3}\pi$.

51. Revolve about the polar axis the part of the cardioid $\rho = 4 + 4 \cos \theta$ between the lines $\theta = 0$ and $\theta = \frac{\pi}{2}$ and compute the volume.

Ans. 160π .

161. Length of a curve. By the *length of a straight line* we commonly mean the number of times we can superpose upon it another straight line employed as a unit of length, as when the carpenter measures the length of a board by making end-to-end applications of his foot rule.

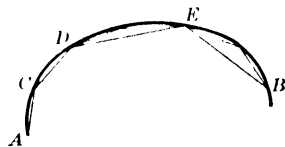
Since it is impossible to make a straight line coincide with an arc of a curve, we cannot measure curves in the same manner as we measure straight lines. We proceed, then, as follows.

Divide the curve (as AB) into any number of parts in any manner whatever (as at C , D , E) and connect the adjacent points of division, forming chords (as AC , CD , DE , EB).

The length of the curve is defined as the limit of the sum of the chords as the number of points of division increases without limit in such a way that at the same time each chord separately approaches zero as a limit.

Since this limit will also be the measure of the length of some straight line, the finding of the length of a curve is also called "the rectification of the curve."

The student has already made use of this definition for the length of a curve in his geometry. Thus the circumference of a circle is defined as the limit of the perimeter of the inscribed (or circumscribed) regular polygon when the number of sides increases without limit.



The method of the next article for finding the length of a plane curve is based on the above definition, and the student should note very carefully how it is applied.

162. Lengths of plane curves; rectangular coördinates. We shall now proceed to express, in analytical form, the definition of the last article, making use of the Fundamental Theorem.

Given the curve $y = f(x)$

and the points $P'(a, c)$, $Q(b, d)$ on it; to find the length of the arc $P'Q$.

FIRST STEP. Take any number n of points on the curve between P' and Q and draw the chords joining the adjacent points, as in the figure. The required length of arc $P'Q$ is evidently the limit of the sum of the lengths of such chords.

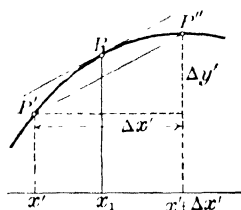
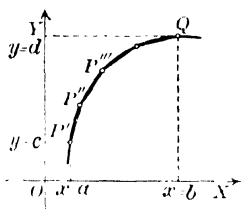
SECOND STEP. Consider any one of these chords, $P'P''$ for example, and let the coördinates of P' and P'' be

$P'(x', y')$ and $P''(x' + \Delta x', y' + \Delta y')$.

Then, as in Art. 95,

$$P'P'' = \sqrt{(\Delta x')^2 + (\Delta y')^2},$$

$$\text{or} \quad P'P'' = \left[1 + \left(\frac{\Delta y'}{\Delta x'} \right)^2 \right]^{\frac{1}{2}} \Delta x'.$$



[Dividing inside the radical by $(\Delta x')^2$ and multiplying outside by $\Delta x'$.]

But from the Theorem of Mean Value (Art. 116) (if $\Delta y'$ is denoted by $f(b) - f(a)$ and $\Delta x'$ by $b - a$), we get

$$\frac{\Delta y'}{\Delta x'} = f'(x_1), \quad (x' < x_1 < x' + \Delta x')$$

x_1 being the abscissa of a point P_1 on the curve between P' and P'' at which the tangent is parallel to the chord.

Substituting, $P'P'' = [1 + f'(x_1)^2]^{\frac{1}{2}} \Delta x' = \text{length of first chord}.$

Similarly, $P''P''' = [1 + f'(x_2)^2]^{\frac{1}{2}} \Delta x'' = \text{length of second chord},$

\dots
 $P^{(n)}Q = [1 + f'(x_n)^2]^{\frac{1}{2}} \Delta x^{(n)} = \text{length of } n\text{th chord}.$

The length of the inscribed broken line joining P' and Q (sum of the chords) is then the sum of these expressions, namely,

$$\begin{aligned} & [1 + f'(x_1)^2]^{\frac{1}{2}} \Delta x' + [1 + f'(x_2)^2]^{\frac{1}{2}} \Delta x'' + \dots + [1 + f'(x_n)^2]^{\frac{1}{2}} \Delta x^{(n)} \\ &= \sum_{i=1}^n [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x^{(i)}. \end{aligned}$$

THIRD STEP. Applying the Fundamental Theorem,

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x^{(1)} = \int_a^b [1 + f'(x)^2]^{\frac{1}{2}} dx.$$

Hence, denoting the length of arc $P'Q$ by s , we have the formula for the length of the arc

$$(G) \quad \begin{aligned} s &= \int_a^b [1 + f'(x)^2]^{\frac{1}{2}} dx, \text{ or} \\ s &= \int_a^b [1 + y'^2]^{\frac{1}{2}} dx, \end{aligned}$$

where $y' = \frac{dy}{dx}$ must be found in terms of x from the equation of the given curve.

Sometimes it is more convenient to use y as the independent variable. To derive a formula to cover this case, we know from Art. 39 that

$$\frac{dy}{dx} = \frac{1}{\frac{dx}{dy}}; \text{ hence } dx = x' dy.$$

Substituting these values in (G), and noting that the corresponding y limits are c and d , we get the formula for the length of the arc,

$$(H) \quad s = \int_c^d [x'^2 + 1]^{\frac{1}{2}} dy,$$

where $x' = \frac{dx}{dy}$ must be found in terms of y from the equation of the given curve.

Formula (G) may be derived in another way. In Art. 95, formula (D),

$$(1) \quad ds = (1 + y'^2)^{\frac{1}{2}} dx$$

gives the differential of the arc of a curve. If we proceed from (1) as in Art. 142, we obtain (G). Also, (H) follows from (E) in Art. 95. Finally, if the curve is defined by parametric equations

$$(2) \quad x = f(t), \quad y = \phi(t),$$

it is convenient to use

$$(3) \quad s = \int (dx^2 + dy^2)^{\frac{1}{2}} = \int_{t_1}^{t_2} [f'^2(t) + \phi'^2(t)]^{\frac{1}{2}} dt,$$

since, from (2), $dx = f'(t)dt$, $dy = \phi'(t)dt$.

ILLUSTRATIVE EXAMPLE 1. Find the length of the circumference of the circle $x^2 + y^2 = r^2$.

Solution. Differentiating, $\frac{dy}{dx} = -\frac{x}{y}$.

Substituting in (G),

$$\begin{aligned}\text{Arc } BA &= \int_0^r \left[1 + \frac{x^2}{y^2} \right]^{\frac{1}{2}} dx \\ &= \int_0^r \left[\frac{y^2 + x^2}{y^2} \right]^{\frac{1}{2}} dx = \int_0^r \left[\frac{r^2}{r^2 - x^2} \right]^{\frac{1}{2}} dx.\end{aligned}$$

[Substituting $y^2 = r^2 - x^2$ from the equation of the circle in order to get everything in terms of x .]

$$\therefore \text{arc } BA = r \int_0^r \frac{dx}{\sqrt{r^2 - x^2}} = \frac{\pi r}{2}. \quad (\text{See Illustrative Example 1, Art. 154.})$$

Hence the total length equals $2 \pi r$. *Ans.*

ILLUSTRATIVE EXAMPLE 2. Find the length of arc of one arch of the cycloid

$$x = a(\theta - \sin \theta), \quad y = a(1 - \cos \theta).$$

See Illustrative Example 2, Art. 81.

Solution. $dx = a(1 - \cos \theta) d\theta$, $dy = a \sin \theta d\theta$.

Then $dx^2 + dy^2 = 2a^2(1 - \cos \theta) d\theta^2 = 4a^2 \sin^2 \frac{1}{2} \theta d\theta^2$. By (5), Art. 2

$$\text{Using (3),} \quad s = \int_0^{2\pi} 2a \sin \frac{1}{2} \theta d\theta = 8a. \quad \text{Ans.}$$

The limits are the values of θ at 0 and 1π see figure, Illustrative Example 2, Art. 81), that is, $\theta = 0$ and $\theta = 2\pi$.

ILLUSTRATIVE EXAMPLE 3. Find the length of the arc of the curve $25y^2 = x^5$ from $x = 0$ to $x = 2$.

Solution. Differentiating, $y' = \frac{1}{2} x^{\frac{3}{2}}$. Hence, by (G),

$$(4) \quad s = \int_0^2 \left(1 + \frac{1}{4} x^3 \right)^{\frac{1}{2}} dx = \frac{1}{2} \int_0^2 (4 + x^3)^{\frac{1}{2}} dx.$$

The integral in (4) was evaluated approximately in Illustrative Example 2, Art. 148, by the trapezoidal rule, and also in Illustrative Example 2, Art. 149, by Simpson's rule. Taking the latter value, $s = \frac{1}{2}(4.821) = 2.41$ linear units. *Ans.*

163. Lengths of plane curves; polar coördinates. From (I), Art. 96, by proceeding as in Art. 142, we get the formula for the length of the arc,

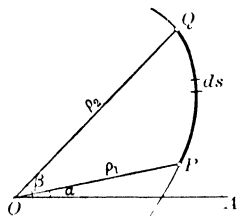
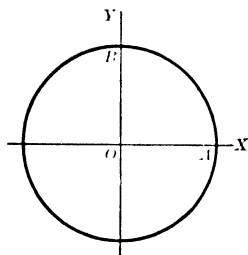
$$(I) \quad s = \int_a^b \left[\rho^2 + \left(\frac{d\rho}{d\theta} \right)^2 \right]^{\frac{1}{2}} d\theta,$$

where ρ and $\frac{d\rho}{d\theta}$ in terms of θ must be substituted from the equation of the given curve.

In case it is more convenient to use ρ as the independent variable, and the equation is in the form

$$\begin{aligned}\theta &= \phi(\rho), \\ d\theta &= \phi'(\rho) d\rho = \frac{d\theta}{d\rho} d\rho.\end{aligned}$$

then



Substituting this in $[\rho^2 d\theta^2 + d\rho^2]^{\frac{1}{2}}$
gives
$$\left[\rho^2 \left(\frac{d\theta}{d\rho} \right)^2 + 1 \right]^{\frac{1}{2}} d\rho.$$

Hence if ρ_1 and ρ_2 are the corresponding limits of the independent variable ρ , we get the formula for the length of the arc,

$$(J) \quad s = \int_{\rho_1}^{\rho_2} \left[\rho^2 \left(\frac{d\theta}{d\rho} \right)^2 + 1 \right]^{\frac{1}{2}} d\rho,$$

where $\frac{d\theta}{d\rho}$ in terms of ρ must be substituted from the equation of the given curve.

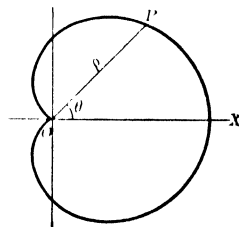
ILLUSTRATIVE EXAMPLE. Find the perimeter of the cardioid $\rho = a(1 + \cos \theta)$.

Solution. Here $\frac{d\rho}{d\theta} = -a \sin \theta$.

If we let θ vary from 0 to π , the point P will generate one half of the curve. Substituting in (I),

$$\begin{aligned} \frac{s}{2} &= \int_0^\pi [a^2(1 + \cos \theta)^2 + a^2 \sin^2 \theta]^{\frac{1}{2}} d\theta \\ &= a \int_0^\pi (2 + 2 \cos \theta)^{\frac{1}{2}} d\theta = 2a \int_0^\pi \cos \frac{\theta}{2} d\theta = 4a. \end{aligned}$$

$\therefore s = 8a$. Ans.



PROBLEMS

1. Find the length of the curve whose equation is $y^3 = x^2$ between the points (0, 0) and (8, 4). Ans. 9.07.

2. Find the length of the arc of the semicubical parabola $ay^2 = x^3$ from the origin to the ordinate $x = 5$. Ans. $\frac{335}{27}a$.

3. Find the length of the curve whose equation is $y = \frac{x^3}{6} + \frac{1}{2x}$ from the point where $x = 1$ to the point where $x = 3$. Ans. $\frac{1}{3}4$.

4. Find the length of the arc of the parabola $y^2 = 2px$ from the vertex to one extremity of the latus rectum. Ans. $\frac{p\sqrt{2}}{2} + \frac{p}{2} \ln(1 + \sqrt{2})$.

5. Find the length of arc of the curve $y^2 = x^3$ from the point where $x = 0$ to the point where $x = \frac{5}{9}$. Ans. $\frac{1}{3}\frac{9}{5}$.

6. Find the length of arc of the parabola $6y = x^2$ from the origin to the point $(4, \frac{8}{3})$. Ans. 4.98.

7. Approximate by Simpson's rule the length of arc of the curve $3y = x^3$ from the origin to the point $(1, \frac{1}{3})$. Ans. 1.09.

8. Find the length of arc of the curve $y = \log \sec x$ from the origin to the point $(\frac{\pi}{3}, \ln 2)$ *Ans.* $\ln(2 + \sqrt{3})$.

9. Find the length of arc of the hyperbola $x^2 - y^2 = 9$ from $(3, 0)$ to $(5, 4)$. *Ans.* 4.56.

10. Find the length of the arch of the parabola $y = 4x - x^2$ which lies above the x -axis. *Ans.* 9.29.

11. Find the entire length of the hypocycloid $x^{\frac{4}{3}} + y^{\frac{4}{3}} = a^{\frac{4}{3}}$. *Ans.* $6a$.

12. Rectify the catenary $y = \frac{a}{2}(e^{\frac{x}{a}} + e^{-\frac{x}{a}})$ from $x = 0$ to the point (x, y) .
Ans. $\frac{a}{2}(e^{\frac{x}{a}} - e^{-\frac{x}{a}})$.

13. Find the length of one complete arch of the cycloid

$$x = r \text{ arc vers } \frac{y}{r} - \sqrt{2ry - y^2}. \quad \text{Ans. } 8r.$$

HINT. Use (H), Art. 162. Here $\frac{dx}{dy} = \frac{y}{\sqrt{2ry - y^2}}$.

14. Rectify the curve $9ay^2 = x(x - 3a)^2$ from $x = 0$ to $x = 3a$.
Ans. $2a\sqrt{3}$.

15. Find the length in one quadrant of the curve $(\frac{x}{a})^{\frac{2}{3}} + (\frac{y}{b})^{\frac{2}{3}} = 1$.
Ans. $\frac{a^2 + ab + b^2}{a + b}$.

16. Find the length between $x = a$ and $x = b$ of the curve $e^y = \frac{e^x + 1}{e^x - 1}$.
Ans. $\log \frac{e^{2b} - 1}{e^{2a} - 1} + a - b$.

17. The equations of the involute of a circle are

$$\begin{cases} x = a(\cos \theta + \theta \sin \theta), \\ y = a(\sin \theta - \theta \cos \theta). \end{cases}$$

Find the length of the arc from $\theta = 0$ to $\theta = \theta_1$. *Ans.* $\frac{1}{2}a\theta_1^2$.

18. Find the length of arc of curve $\begin{cases} x = e^{\theta} \sin \theta \\ y = e^{\theta} \cos \theta \end{cases}$ from $\theta = 0$ to $\theta = \frac{\pi}{2}$.
Ans. $\sqrt{2}(e^{\frac{\pi}{2}} - 1)$.

Find the length of arc of each of the following curves.

19. $y = \ln(1 - x^2)$ from $x = 0$ to $x = \frac{1}{2}$.

20. $y = \frac{x^2}{4} - \frac{1}{2} \ln x$ from $x = 1$ to $x = 2$.

21. $y = \ln \csc x$ from $x = \frac{\pi}{6}$ to $x = \frac{\pi}{2}$.

22. $3x^2 = y^3$ from $y = 1$ to $y = 20$.

23. One arch of the curve $y = \sin x$.

24. Find the length of the spiral of Archimedes, $\rho = a\theta$, from the origin to the end of the first revolution.

$$\text{Ans. } \pi a \sqrt{1 + 4\pi^2} + \frac{a}{2} \ln(2\pi + \sqrt{1 + 4\pi^2}).$$

25. Rectify the spiral $\rho = e^{a\theta}$ from the origin to the point (ρ, θ) .

HINT. Use (J) .

$$\text{Ans. } \frac{\rho}{a} \sqrt{a^2 + 1}.$$

26. Find the length of the curve $\rho = a \sec^2 \frac{\theta}{2}$ from $\theta = 0$ to $\theta = \frac{\pi}{2}$.

$$\text{Ans. } [\sqrt{2} + \ln(\sqrt{2} + 1)]a.$$

27. Find the length of arc of the parabola $\rho = \frac{2}{1 + \cos \theta}$ from $\theta = 0$ to $\theta = \frac{\pi}{2}$.

$$\text{Ans. } \sqrt{2} + \ln(\sqrt{2} + 1).$$

28. Find the length of the hyperbolic spiral $\rho\theta = a$ from (ρ_1, θ_1) to (ρ_2, θ_2) .

$$\text{Ans. } \sqrt{a^2 + \rho_1^2} - \sqrt{a^2 + \rho_2^2} - a \ln \frac{\rho_1(a + \sqrt{a^2 + \rho_2^2})}{\rho_2(a + \sqrt{a^2 + \rho_1^2})}.$$

29. Show that the entire length of the curve $\rho = a \sin^3 \frac{\theta}{3}$ is $\frac{3}{2} \pi a$. Show that OA, AB, BC (see figure) are in arithmetical progression.

30. Find the length of arc of the cissoid $\rho = 2a \tan \theta \sin \theta$ from $\theta = 0$ to $\theta = \frac{\pi}{4}$.

31. Approximate the perimeter of one leaf of the curve $\rho = \sin 2\theta$.

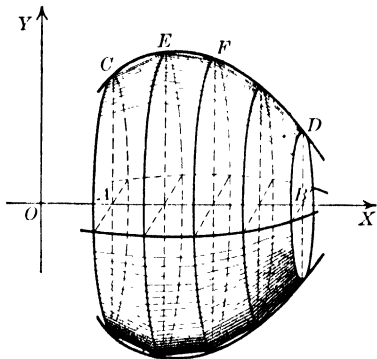
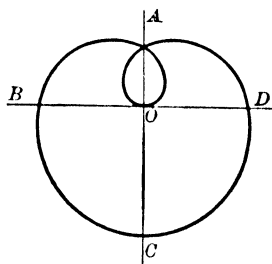
164. Areas of surfaces of revolution. A surface of revolution is generated by revolving the arc CD of the curve

$$y = f(x)$$

about the axis of X .

It is desired to measure the area of this surface by making use of the Fundamental Theorem.

FIRST STEP. As before, divide the interval AB into subintervals $\Delta x_1, \Delta x_2$, etc., and erect ordinates at the points of division. Draw the chords CE, EF , etc. of the curve. When the curve is revolved, each chord generates the lateral surface of a frustum of a cone of revolution. The area of the required



surface of revolution is defined as the limit of the sum of the lateral areas of these frustums.

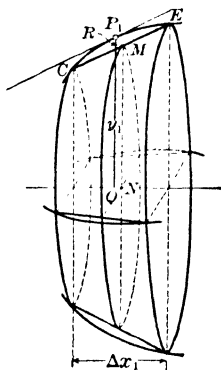
SECOND STEP. For the sake of clearness let us draw the first frustum on a larger scale. Let M be the middle point of the chord CE . Then

$$(1) \quad \text{Lateral area} = 2 \pi NM \cdot CE.*$$

In order to apply the Fundamental Theorem it is necessary to express this product as a function of the abscissa of some point in the interval Δx_1 . As in Art. 162, we get, using the Theorem of Mean Value, the length of the chord

$$(2) \quad CE = [1 + f'(x_1)^2]^{\frac{1}{2}} \Delta x_1,$$

where x_1 is the abscissa of the point $P_1(x_1, y_1)$ on the arc CE where the tangent is parallel to the chord CE . Let the horizontal line through M intersect QP_1 (the ordinate of P_1) at R , and denote RP_1 by ϵ_1 .†



$$(3) \quad NM = y_1 - \epsilon_1.$$

Substituting (2) and (3) in (1), we get

$$2 \pi (y_1 - \epsilon_1) [1 + f'(x_1)^2]^{\frac{1}{2}} \Delta x_1 = \text{lateral area of first frustum.}$$

Similarly,

$$2 \pi (y_2 - \epsilon_2) [1 + f'(x_2)^2]^{\frac{1}{2}} \Delta x_2 = \text{lateral area of second frustum,}$$

.

$$2 \pi (y_n - \epsilon_n) [1 + f'(x_n)^2]^{\frac{1}{2}} \Delta x_n = \text{lateral area of last frustum.}$$

Hence

$$\sum_{i=1}^n 2 \pi (y_i - \epsilon_i) [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x_i = \text{sum of lateral areas of frustums.}$$

This may be written

$$(4) \quad \sum_{i=1}^n 2 \pi y_i [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x_i - 2 \pi \sum_{i=1}^n \epsilon_i [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x_i.$$

* The lateral area of the frustum of a cone of revolution is equal to the circumference of the middle section multiplied by the slant height.

† The student will observe that as Δx_1 approaches zero as a limit, ϵ_1 also approaches the limit zero.

THIRD STEP. Applying the Fundamental Theorem to the first sum (using the limits $OA = a$ and $OB = b$), we get

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n 2 \pi y_i [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x_i = \int_a^b 2 \pi y [1 + f'(x)^2]^{\frac{1}{2}} dx.$$

The limit of the second sum of (4) when $n \rightarrow \infty$ is zero.* Hence the area of the surface of revolution generated by revolving the arc CD about OX is given by the formula

$$(K) \quad S_x = 2 \pi \int_a^b y \left[1 + \left(\frac{dy}{dx} \right)^2 \right]^{\frac{1}{2}} dx,$$

where S_x denotes the required area. Or we may write the formula in the form

$$(L) \quad S = 2 \pi \int_a^b y \, ds.$$

Similarly, when OY is the axis of revolution we use the formula

$$(M) \quad S_y = 2 \pi \int_c^d x \, ds.$$

In (L) and (M) ds will have one of the three forms (C), (D), (E), of Art. 95, namely,

$$ds = \left[1 + \left(\frac{dy}{dx} \right)^2 \right]^{\frac{1}{2}} dx = \left[1 + \left(\frac{dx}{dy} \right)^2 \right]^{\frac{1}{2}} dy = (dx^2 + dy^2)^{\frac{1}{2}},$$

depending upon the choice of the independent variable. The last form must be used when the given curve is defined by parametric equations. In using (L) or (M), calculate ds first.

The formula (L) is easily remembered if we consider a narrow band of the surface included between two planes perpendicular to the axis of revolution, and regard it approximately as the convex surface of a frustum of a cone of revolution of slant height ds , with a middle section whose circumference equals $2 \pi y$, and hence of area $2 \pi y \, ds$.

ILLUSTRATIVE EXAMPLE 1. The arc of the cubical parabola

$$(5) \quad a^2 y = x^3$$

between $x = 0$ and $x = a$ is revolved about OX . Find the area of the surface of revolution generated.

* This is easily seen as follows. Denote the second sum by S_n . If ϵ equals the largest of the positive numbers $|\epsilon_1|, |\epsilon_2|, \dots, |\epsilon_n|$, then

$$S_n \leq \epsilon \sum_{i=1}^n [1 + f'(x_i)^2]^{\frac{1}{2}} \Delta x_i.$$

The sum on the right is, by Art. 162, equal to the sum of the chords CE, EF , etc. Let this sum be l_n . Then $S_n \leq \epsilon l_n$. Since $\lim_{n \rightarrow \infty} \epsilon = 0$, S_n is an infinitesimal, and therefore $\lim_{n \rightarrow \infty} S_n = 0$.

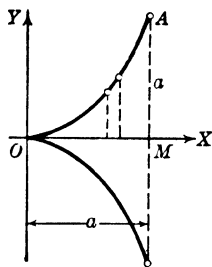
Solution. From (5), $y' = \frac{3x^2}{a^2}$. Hence

$$ds = (1 + y'^2)^{\frac{1}{2}} dx = \frac{1}{a^2} (a^4 + 9x^4)^{\frac{1}{2}} dx.$$

Then the element of area $= 2\pi y ds = \frac{2\pi}{a^4} (a^4 + 9x^4)^{\frac{1}{2}} x^3 dx$.

Therefore, by (L),

$$\begin{aligned} S_x &= \frac{2\pi}{a^4} \int_0^a (a^4 + 9x^4)^{\frac{1}{2}} x^3 dx = \frac{\pi}{27a^4} \left[(a^4 + 9x^4)^{\frac{3}{2}} \right]_0^a \\ &= \frac{\pi}{27} (10\sqrt{10} - 1)a^2 = 3.6a^2. \text{ Ans.} \end{aligned}$$



ILLUSTRATIVE EXAMPLE 2. Find the area of the ellipsoid of revolution generated by revolving the ellipse whose parametric equations are (see (3), Art. 81) $x = a \cos \phi$, $y = b \sin \phi$ about OX .

Solution. We have

$$dx = -a \sin \phi d\phi, \quad dy = b \cos \phi d\phi,$$

and

$$ds = (dx^2 + dy^2)^{\frac{1}{2}} = (a^2 \sin^2 \phi + b^2 \cos^2 \phi)^{\frac{1}{2}} d\phi.$$

Hence the element of area $= 2\pi y ds = 2\pi b(a^2 \sin^2 \phi + b^2 \cos^2 \phi)^{\frac{1}{2}} \sin \phi d\phi$.

$$(6) \quad \therefore \frac{1}{2} S_x = 2\pi b \int_0^{\frac{\pi}{2}} (a^2 \sin^2 \phi + b^2 \cos^2 \phi)^{\frac{1}{2}} \sin \phi d\phi.$$

To integrate, let $u = \cos \phi$. Then $du = -\sin \phi d\phi$. Also,

$$a^2 \sin^2 \phi + b^2 \cos^2 \phi = a^2(1 - \cos^2 \phi) + b^2 \cos^2 \phi = a^2 - (a^2 - b^2)u^2.$$

Hence, using the new limits $u = 1$, $u = 0$, and interchanging the u limits (Art. 150), the result is

$$\frac{1}{2} S_x = 2\pi b \int_0^1 [a^2 - (a^2 - b^2)u^2]^{\frac{1}{2}} du. \quad (a > b)$$

Working this out by (22), we get

$$S_x = 2\pi b^2 + \frac{2\pi ab}{e} \text{ arc sin } e, \text{ where } e = \text{eccentricity} = \frac{\sqrt{a^2 - b^2}}{a}. \text{ Ans.}$$

ILLUSTRATIVE EXAMPLE 3. Find the area of the surface of revolution generated by revolving the hypocycloid $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$ about the x -axis.

Solution. Here $\frac{dy}{dx} = -\frac{y^{\frac{1}{3}}}{x^{\frac{1}{3}}}$, $y = (a^{\frac{2}{3}} - x^{\frac{2}{3}})^{\frac{3}{2}}$;

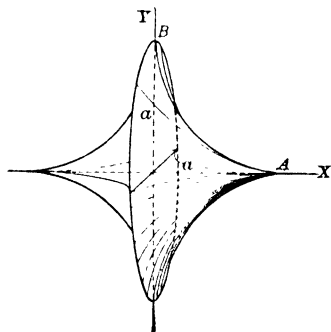
$$ds = \left(1 + \frac{y^{\frac{2}{3}}}{x^{\frac{2}{3}}} \right)^{\frac{1}{2}} dx = \left(\frac{x^{\frac{2}{3}} + y^{\frac{2}{3}}}{x^{\frac{2}{3}}} \right)^{\frac{1}{2}} = \frac{a^{\frac{1}{3}}}{x^{\frac{1}{3}}} dx.$$

Substituting in (L), noting that the arc BA generates only one half of the surface, we get

$$\frac{S_x}{2} = 2\pi a^{\frac{1}{3}} \int_0^a (a^{\frac{2}{3}} - x^{\frac{2}{3}})^{\frac{3}{2}} x^{-\frac{1}{3}} dx.$$

This is an improper integral, since the function to be integrated is discontinuous (becomes infinite) when $x = 0$. Using the definition (1), Art. 154, the result is

$$\frac{S_x}{2} = \frac{6\pi a^2}{5}. \quad \therefore S_x = \frac{12\pi a^2}{5}.$$



PROBLEMS

1. Find by integration the area of the surface of the sphere generated by revolving the circle $x^2 + y^2 = r^2$ about a diameter. *Ans.* $4\pi r^2$.

2. Find by integration the area of the surface of the cone generated by revolving about OX the line joining the origin to the point (a, b) .

Ans. $\pi b\sqrt{a^2 + b^2}$.

3. Find by integration the area of the surface of the cone generated by revolving the line $y = 2x$ from $x = 0$ to $x = 2$ (a) about OX ; (b) about OY . Verify your results geometrically.

4. Find by integration the lateral area of the frustum of a cone generated by revolving about OX the line $2y = x - 4$ from $x = 0$ to $x = 5$. Verify your result geometrically.

5. Find the area of the surface generated by revolving about OY the arc of the parabola $y = x^2$ from $y = 0$ to $y = 2$. *Ans.* $\frac{1}{3}\pi$.

6. Find the area of the surface generated by revolving about OX the arc of the parabola $y = x^2$ from $(0, 0)$ to $(2, 4)$.

7. Find the area of the surface generated by revolving about OX the arc of the parabola $y^2 = 4 - x$ which lies in the first quadrant. *Ans.* 36.18 .

8. Find the area of the surface generated by revolving about OX the arc of the parabola $y^2 = 2px$ from $x = 0$ to $x = 4p$. *Ans.* $\frac{5}{3}\pi p^2$.

9. Find the area of the surface generated by revolving about OY the arc of $y = x^3$ from $(0, 0)$ to $(2, 8)$.

Find the area of the surface generated by revolving each of the following curves about OX .

10. $y = x^3$, from $x = 0$ to $x = 2$. *Ans.* $\frac{8}{3}\pi$.

11. $y^2 = 9x$, from $x = 0$ to $x = 4$. 49π .

12. $y^2 = 24 - 4x$, from $x = 3$ to $x = 6$. $\frac{5}{3}\pi$.

13. $6y = x^2$, from $x = 0$ to $x = 4$. $\frac{(820 - 81 \ln 3)\pi}{72}$.

14. $y = e^{-x}$, from $x = 0$ to $x = \infty$. $\pi[\sqrt{2} + \ln(1 + \sqrt{2})]$.

15. The loop of $9ay^2 = x(3a - x)^2$. $3\pi a^2$.

16. $6a^2xy = x^4 + 3a^4$, from $x = a$ to $x = 2a$. $\frac{47}{16}\pi a^2$.

17. One loop of $8a^2y^2 = a^2x^2 - x^4$. $\frac{1}{4}\pi a^2$.

18. $y^2 + 4x = 2 \log y$, from $y = 1$ to $y = 2$. $\frac{1}{3}\pi$.

19. The cycloid $\begin{cases} x = a(\theta - \sin \theta), \\ y = a(1 - \cos \theta). \end{cases}$ *Ans.* $\frac{64}{3}\pi a^2$.

20. The cardioid $\begin{cases} x = a(2 \cos \theta - \cos 2 \theta), \\ y = a(2 \sin \theta - \sin 2 \theta). \end{cases}$ $\frac{128}{5}\pi a^2$.

21. $y^2 = 4x$, from $x = 0$ to $x = 3$.

22. $x^2 + y^2 = 4$, from $x = 1$ to $x = 2$.

23. $x^2 + 4y^2 = 36$.

24. $9x^2 + 4y^2 = 36$.

Find the area of the surface generated by revolving each of the following curves about OY .

25. $x = y^3$, from $y = 0$ to $y = 3$. *Ans.* $\frac{1}{2} \pi [(730)^{\frac{3}{2}} - 1]$.

26. $y = x^3$, from $y = 0$ to $y = 3$.

27. $6a^2xy = x^2 + 3a^1$, from $x = a$ to $x = 3a$. $(20 + \ln 3)\pi a^2$.

28. $4y = x^2 - 2 \ln x$, from $x = 1$ to $x = 4$. 24 π .

29. $2y = x\sqrt{x^2 - 1} + \log(x - \sqrt{x^2 - 1})$, from $x = 2$ to $x = 5$. *Ans.* 78 π .

30. $y^2 = x^4$, from $x = 0$ to $x = 8$. 713.

31. $4y = x^2$, from $y = 0$ to $y = 4$. 33. $4x^2 + y^2 = 64$.

32. $x^2 + 4y^2 = 16$. 34. $9x = y^3$, from $y = 0$ to $y = 3$.

Find the area of the surface generated by revolving each of the following curves.

*About OX**About OY*

35. The ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$. $2\pi a^2 + \frac{\pi b^2}{e} \ln \frac{1+e}{1-e}$.

HINT. e = eccentricity of ellipse

$$= \frac{\sqrt{a^2 - b^2}}{a}.$$

36. The catenary $y = \frac{a}{2}(e^{\frac{x}{a}} + e^{-\frac{x}{a}})$,

from $x = 0$ to $x = a$. $\frac{\pi a^2}{4}(e^2 + 4 - e^{-2})$. $2\pi a^2(1 - e^{-1})$.

(Figure, p. 532)

37. $x^4 + 3 = 6xy$, from $x = 1$ to $x = 2$. $\frac{17}{16}\pi$. $\pi(\frac{1}{4} + \ln 2)$.

38. $\left\{ \begin{array}{l} x = e^\theta \sin \theta, \\ y = e^\theta \cos \theta, \end{array} \right\}$ from $\theta = 0$ to $\frac{\pi}{2}$. $\frac{2\sqrt{2}\pi}{5}(e^\pi - 2)$. $\frac{2\sqrt{2}\pi}{5}(2e^\pi + 1)$.

39. $3x^2 + 4y^2 = 3a^2$. $(\frac{3}{2} + \frac{\pi}{\sqrt{3}})\pi a^2$. $(4 + 3 \ln 3)\frac{\pi a^2}{2}$.

40. The slope of the tractrix at any point of the curve in the first quadrant is given by $\frac{dy}{dx} = \frac{-y}{\sqrt{c^2 - y^2}}$. Show that the surface generated by revolving about OX the arc joining the points (x_1, y_1) and (x_2, y_2) on the tractrix is $2\pi c(y_1 - y_2)$. (Figure, p. 537)

41. The area in the first quadrant bounded by the curves whose equations are $y = x^3$ and $y = 4x$ is revolved about OX . Find the total surface of the solid generated. *Ans.* 410.3.

42. The area bounded by the y -axis and the curves whose equations are $x^2 = 4y$ and $x - 2y + 4 = 0$ is revolved about OY . Find the total surface of the solid generated. Ans. 141.5.

43. Find the surface generated by revolving about OX the arc of the curve whose equation is $y = \frac{x^3}{6} + \frac{1}{2x}$ from $x = 1$ to $x = 3$. Ans. $\frac{208\pi}{9}$.

44. Find the entire surface of the solid generated by revolving about OX the area bounded by the two parabolas $y^2 = 4x$ and $y^2 = x + 3$.

Ans. $\frac{1}{6}\pi(17\sqrt{17} + 32\sqrt{2} - 17) = 51.53$.

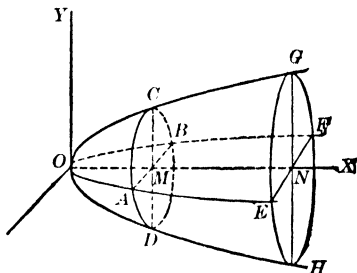
45. Find the area of the surface generated by revolving about OX one arch of the curve $y = \sin x$. Ans. 14.42.

165. Solids with known parallel cross sections. In Art. 160 we discussed the volume of a solid of revolution, such as is shown in the accompanying figure. All cross sections in planes perpendicular to the x -axis are circles. If $OM = x$, $MC = y$, then

(1) Area cross section

$$ACBD = \pi y^2 = \pi [\phi(x)]^2,$$

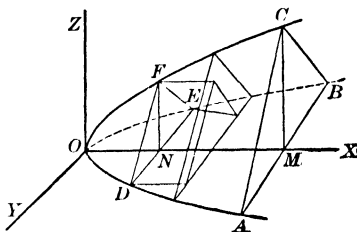
if $y = \phi(x)$ is the equation of the generating curve OCG . Hence the area of the cross section in any plane perpendicular to OX is a function of its perpendicular distance ($= x$) from the point O .



We shall now discuss the calculation of volumes of solids that are not solids of revolution when it is possible to express the area of any plane section of the solid which is perpendicular to a fixed line (as OX) as a function of its distance from a fixed point (as O).

Divide the solid into n slices by equidistant sections perpendicular to OX , each of thickness Δx .

Let FDE be one face of such a slice, and let $ON = x$. Then, by hypothesis,



$$(2) \quad \text{Area } FDE = A(x).$$

The volume of this slice is equal, approximately, to

$$(3) \quad \text{Area } FDE \times \Delta x = A(x)\Delta x \text{ (base} \times \text{altitude).}$$

Then $\sum_{i=1}^n A(x_i) \Delta x_i =$ sum of volumes of all such prisms. It is evident that the required volume is the limit of this sum; hence, by the Fundamental Theorem,

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n A(x_i) \Delta x_i = \int A(x) dx,$$

and we have the formula

$$(N) \quad V = \int A(x) dx,$$

where $A(x)$ is defined in (2).

The element of volume is a prism (in some cases a cylinder) whose altitude is dx and whose base has the area $A(x)$. That is,

$$dV = A(x) dx.$$

ILLUSTRATIVE EXAMPLE 1. The base of a solid is a circle of radius r . All sections perpendicular to a fixed diameter of the base are squares. Find the volume of the solid.

Solution. Take the circle $x^2 + y^2 = r^2$ in the XY -plane as base, and OX as the fixed diameter. Then the section $PQRS$ perpendicular to OX is a square of area $4y^2$, if $PQ = 2y$. (In the figure, the portion of the solid on the right of the section $PQRS$ is omitted.)

Hence $A(x) = 4y^2 = 4(r^2 - x^2)$, and, by (N),

$$\text{Volume} = 4 \int_{-r}^r (r^2 - x^2) dx = \frac{16}{3} r^3. \text{ Ans.}$$

ILLUSTRATIVE EXAMPLE 2. Find the volume of a right conoid with circular base, the radius of the base being r and the altitude a .

Solution. Placing the conoid as shown in the figure, consider a section PQR perpendicular to OX . This section is an isosceles triangle; and, since

$$RM = \sqrt{2rx - x^2}$$

(found by solving $x^2 + y^2 = 2rx$, the equation of the circle $ORAQ$, for y) and

$$MP = a,$$

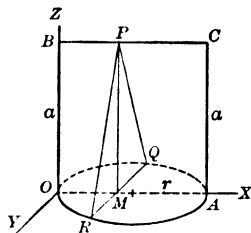
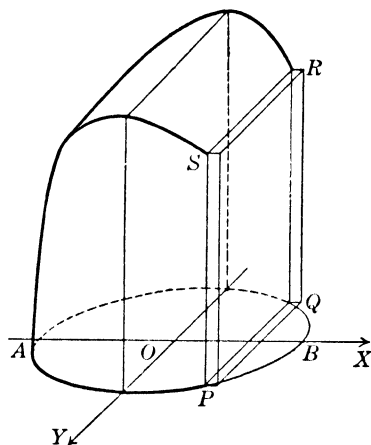
the area of the section is

$$a \sqrt{2rx - x^2} = A(x).$$

Substituting in (N),

$$V = a \int_0^{2r} \sqrt{2rx - x^2} dx = \frac{\pi r^2 a}{2}. \text{ Ans.}$$

This is one half the volume of the cylinder of the same base and altitude.



ILLUSTRATIVE EXAMPLE 3. Calculate the volume of the ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

by a single integration.

Solution. Consider a section of the ellipsoid perpendicular to OX , as $ABCD$, with semiaxes b' and c' . The equation of the ellipse $HEJG$ in the XOY -plane is

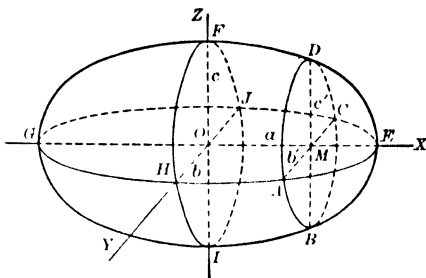
$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1.$$

Solving this for y ($= b'$) in terms of x ($= OM$) gives

$$b' = \frac{b}{a} \sqrt{a^2 - x^2}.$$

Similarly, from the equation of the ellipse $EFGI$ in the XOZ -plane we get

$$c' = \frac{c}{a} \sqrt{a^2 - x^2}.$$



Hence the area of the ellipse (section) $ABCD$ is

$$\pi b' c' = \frac{\pi bc}{a^2} (a^2 - x^2) = A(x).$$

Substituting in (N),

$$V = \frac{\pi bc}{a^2} \int_{-a}^{+a} (a^2 - x^2) dx = \frac{4}{3} \pi abc. \text{ Ans.}$$

PROBLEMS

1. A solid has a circular base of radius r . The line AB is a diameter of the base. Find the volume of the solid if every plane section perpendicular to AB is

(a) an equilateral triangle; Ans. $\frac{1}{3} r^3 \sqrt{3}$.

(b) an isosceles right triangle with its hypotenuse in the plane of the base; Ans. $\frac{1}{3} r^3$.

(c) an isosceles right triangle with one leg in the plane of the base; Ans. $\frac{8}{3} r^3$.

(d) an isosceles triangle with its altitude equal to 20 in.; Ans. $10 \pi r^2$.

(e) an isosceles triangle with its altitude equal to its base. Ans. $\frac{8}{3} r^3$.

2. A solid has a base in the form of an ellipse with major axis 20 in. long and minor axis 10 in. long. Find the volume of the solid if every section perpendicular to the major axis is

(a) a square; Ans. 1,333 cu. in.

(b) an equilateral triangle; 577.3 cu. in.

(c) an isosceles triangle with altitude 10 in. 785.4 cu. in.

3. The base of a solid is a segment of a parabola cut off by a chord perpendicular to its axis. The chord has a length of 16 in. and is distant 8 in. from the vertex of the parabola. Find the volume of the solid if every section perpendicular to the axis of the base is

- (a) a square; *Ans.* 1024 cu. in.
 (b) an equilateral triangle; 443.4 cu. in.
 (c) an isosceles triangle with altitude 10 in. 426.7 cu. in.

4. A football is 16 in. long, and a plane section containing a seam is an ellipse, the shorter diameter of which is 8 in. Find the volume (a) if the leather is so stiff that every cross section is a square; (b) if the cross section is a circle. *Ans.* (a) $341\frac{1}{3}$ cu. in.; (b) 535.9 cu. in.

5. A wedge is cut from a cylinder of radius 5 in. by two planes, one perpendicular to the axis of the cylinder and the other passing through a diameter of the section made by the first plane and inclined to this plane at an angle of 45° . Find the volume of the wedge. *Ans.* $2\frac{2}{3}\pi$ cu. in.

6. Two cylinders of equal radius r have their axes meeting at right angles. Find the volume of the common part. *Ans.* $\frac{16}{3}r^3$.

7. A circle of radius a moves with its center on the circumference of an equal circle, and keeps parallel to a given plane which is perpendicular to the plane of the given circle. Find the volume of the solid it will generate. *Ans.* $\frac{2}{3}a^3(3\pi + 8)$.

8. A variable equilateral triangle moves with its plane perpendicular to the x -axis and the ends of its base on the points on the curves $y^2 = 16ax$ and $y^2 = 4ax$, respectively, above the x -axis. Find the volume generated by the triangle as it moves from the origin to the points whose abscissa is a . *Ans.* $\frac{1}{2}\sqrt{3}a^3$.

9. A rectangle moves from a fixed point, one side being always equal to the distance from this point, and the other equal to the square of this distance. What is the volume generated while the rectangle moves a distance of 2 ft.? *Ans.* 4 cu. ft.

10. On the double ordinates of the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$, isosceles triangles of vertical angle 90° are described in planes perpendicular to that of the ellipse. Find the volume of the solid generated by supposing such a variable triangle moving from one extremity to the other of the major axis of the ellipse. *Ans.* $\frac{4}{3}ab^2$.

Calculate the volumes bounded by the following quadric surfaces and the given planes.

11. $z = x^2 + 4y^2$; $z = 1$. *Ans.* $\frac{1}{4}\pi$.
 12. $4x^2 + 9z^2 + y = 0$; $y + 1 = 0$. $\frac{1}{12}\pi$.
 13. $x^2 + 4y^2 = 1 + z^2$; $z + 1 = 0$; $z - 1 = 0$. $\frac{4}{3}\pi$.
 14. $25y^2 + 9z^2 = 1 + x^2$; $x = 0$; $x = 2$. $\frac{1}{4}\frac{2}{3}\pi$.

$$15. x^2 + 4y^2 + 9z^2 = 1. \quad \text{Ans. } \frac{8}{3}\pi.$$

$$16. z^2 = x^2 + 9y^2; z + 1 = 0. \quad \frac{1}{3}\pi.$$

17. Given the parabola $z = 4 - x^2$ in the XZ -plane and the circle $x^2 + y^2 = 4$ in the XY -plane. From each point on the parabola lying above the circle two lines are drawn parallel to the YZ -plane to meet the circle. Calculate the volume of the wedge-shaped solid thus formed.

Ans. 6π .

18. Find the volume of the solid bounded by the hyperboloid of one sheet $\frac{z^2}{c^2} = \frac{x^2}{a^2} - \frac{y^2}{b^2} + 1$ and the planes $x = 0, x = a$. Ans. $\frac{1}{3}\pi abc$.

19. A solid is bounded by one nappe of the hyperboloid of two sheets $\frac{z^2}{c^2} = \frac{x^2}{a^2} - \frac{y^2}{b^2} - 1$ and the plane $x = 2a$. Find the volume. Ans. $\frac{1}{3}\pi abc$.

20. Find the volume of the solid bounded by the surface

$$\frac{x^4}{a^4} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1. \quad \text{Ans. } \frac{8}{3}\pi abc.$$

ADDITIONAL PROBLEMS

1. Find the area of the loop of the curve

$$y^2 = (x + 4)(x^2 - x + 2y - 4). \quad \text{Ans. } \frac{256}{15}.$$

2. A point moves along a parabola in such a way that the radius joining it to the focus generates area at a constant rate. If the point moves from the vertex to one end of the latus rectum in 1 sec., what will be its position at the end of the next 8 sec.?

Ans. Distance from focus = $\frac{1}{2}$ latus rectum.

3. Find the perimeter of the figure bounded by the line $y = 1$ and the curve $4y = e^{2x} + e^{-2x}$. Ans. $\sqrt{3} + \ln(2 + \sqrt{3}) = 3.05$.

4. The arc OP of the curve $xy = x - y$ joins the origin to the point $P(x_1, y_1)$, and bounds with the x -axis and the line $x = x_1$ an area A . The same arc bounds with the y -axis and the line $y = y_1$ an area B . Prove that the volumes obtained by revolving A about the x -axis and B about the y -axis are equal.

5. The area bounded by the curve $16y^2 = (x + 4)^3$ and its tangent at the point $(12, 16)$ is revolved about the x -axis. Find the volume inclosed. Ans. $\frac{1024}{9}\pi$.

6. The base of a solid is the area bounded by the parabola $y^2 = 2px$ and its latus rectum. Every section of the solid made by a plane at right angles to the latus rectum is a rectangle whose altitude is equal to the distance of the section from the axis of the parabola. Find the volume of the solid. Ans. $\frac{1}{4}p^3$.

7. Given the ellipse $9x^2 + 25y^2 = 225$. A solid is formed about this curve in such a way that all plane sections perpendicular to the x -axis are ellipses whose foci are on the given ellipse. The major and minor axes of each section are proportional to those of the given ellipse. Find the volume of the solid.

Ans. $\frac{225}{4}\pi$.

8. Let (x, y) be a point on the curve of Art. 159, O being the origin and OA the x -axis. Show that (D) may be written

$$(1) \quad \text{Area} = \frac{1}{2} \int (x dy - y dx),$$

by using the transformation (5), p. 4. The limits are determined by the coordinates of the extremities of the curve.

9. Derive the formula of the preceding problem directly from a figure, making use of (B) and (C), Art. 158.

The formula (1) of Problem 8 is useful for parametric equations. Find the following areas by (1).

10. The area between the involute of a circle

$$x = r \cos \theta + r\theta \sin \theta, \quad y = r \sin \theta - r\theta \cos \theta$$

and the x -axis produced to the left, in the figure of Chapter XXVI, p. 537.

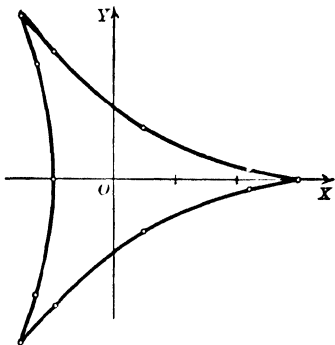
11. The entire area of the hypocycloid of three cusps

$$\begin{cases} x = 2r \cos \theta + r \cos 2\theta, \\ y = 2r \sin \theta - r \sin 2\theta. \end{cases}$$

(See figure.)

Ans. $2\pi r^2$.

12. A straight uniform wire attracts a particle P according to the law of gravitation. The particle is in the line of the wire but not in the wire. Prove that the wire attracts the particle as if the mass of the wire were concentrated at a point of the wire whose distance from P is the mean proportional of the distances from P to the ends of the wire.

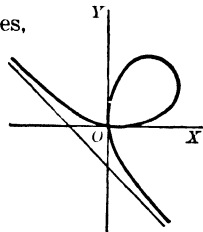


13. Find the area of the loop of the folium of Descartes, $x^3 + y^3 = 3axy$.

HINT. Let $y = tx$; then $x = \frac{3at}{1+t^3}$,

$$y = \frac{3at^2}{1+t^3}, \quad \text{and} \quad dx = \frac{1-2t^4}{(1+t^3)^2} 3a dt.$$

The limits for t are 0 and ∞ .



CHAPTER XVI

FORMAL INTEGRATION BY VARIOUS DEVICES

166. Introduction. Formal integration depends ultimately upon the use of a table of integrals. If, in a given case, no formula is found in the table resembling the given integral, it is often possible to transform the latter so as to make it depend upon formulas in the tables. The devices which may be used are

- (a) *integration by parts* (Art. 136),
- (b) *application of the theory of rational fractions*,
- (c) *use of a suitable substitution*.

We proceed to discuss (b) and (c).

167. Integration of rational fractions. A rational fraction is a fraction the numerator and denominator of which are integral rational functions, that is, the variable is not affected with negative or fractional exponents. If the degree of the numerator is equal to or greater than that of the denominator, the fraction may be reduced to a mixed quantity by dividing the numerator by the denominator. For example,

$$\frac{x^4 + 3x^3}{x^2 + 2x + 1} = x^2 + x - 3 + \frac{5x + 3}{x^2 + 2x + 1}.$$

The last term is a fraction reduced to its lowest terms, having the degree of the numerator less than that of the denominator. It readily appears that the other terms are at once integrable, and hence we need consider only the fraction.

In order to integrate a differential expression involving such a fraction, it is often necessary to resolve it into simpler partial fractions, that is, to replace it by the algebraic sum of fractions of forms such that we can complete the integration. That this is always possible when the denominator can be broken up into its real prime factors is shown in algebra.*

Case I. *When the factors of the denominators are all of the first degree and none are repeated.*

* See Chapter XX in Hawkes's "Advanced Algebra" (Ginn and Company, Boston).

To each nonrepeated linear factor, such as $x - a$, there corresponds a partial fraction of the form

$$\frac{A}{x - a},$$

where A is a constant. The given fraction can be expressed as a sum of fractions of this form. The examples show the method.

ILLUSTRATIVE EXAMPLE. Find $\int \frac{(2x+3)dx}{x^3+x^2-2x}$.

Solution. The factors of the denominator being x , $x-1$, $x+2$, we assume*

$$(1) \quad \frac{2x+3}{x(x-1)(x+2)} = \frac{A}{x} + \frac{B}{x-1} + \frac{C}{x+2},$$

where A , B , C are constants to be determined.

Clearing (1) of fractions, we get

$$(2) \quad \begin{aligned} 2x+3 &= A(x-1)(x+2) + B(x+2)x + C(x-1)x, \\ 2x+3 &= (A+B+C)x^2 + (A+2B-C)x - 2A. \end{aligned}$$

Since this equation is an identity, we equate the coefficients of the like powers of x in the two members according to the method of Undetermined Coefficients, and obtain three simultaneous equations

$$(3) \quad \begin{cases} A+B+C=0, \\ A+2B-C=2, \\ -2A=3. \end{cases}$$

Solving equations (3), we get

$$A = -\frac{3}{2}, \quad B = \frac{5}{3}, \quad C = -\frac{1}{6}.$$

Substituting these values in (1),

$$\begin{aligned} \frac{2x+3}{x(x-1)(x+2)} &= -\frac{3}{2x} + \frac{5}{3(x-1)} - \frac{1}{6(x+2)}, \\ \therefore \int \frac{2x+3}{x(x-1)(x+2)} dx &= -\frac{3}{2} \int \frac{dx}{x} + \frac{5}{3} \int \frac{dx}{x-1} - \frac{1}{6} \int \frac{dx}{x+2} \\ &= -\frac{3}{2} \ln x + \frac{5}{3} \ln (x-1) - \frac{1}{6} \ln (x+2) + \ln c \\ &= \ln \frac{c(x-1)^{\frac{5}{3}}}{x^{\frac{3}{2}}(x+2)^{\frac{1}{6}}}. \quad \text{Ans.} \end{aligned}$$

A shorter method of finding the values of A , B , and C from (2) is the following:

Let factor $x = 0$; then $3 = -2A$, or $A = -\frac{3}{2}$.

Let factor $x-1 = 0$, or $x = 1$; then $5 = 3B$, or $B = \frac{5}{3}$.

Let factor $x+2 = 0$, or $x = -2$; then $-1 = 6C$, or $C = -\frac{1}{6}$.

In every example in rational fractions the *number of constants to be determined is equal to the degree of the denominator*.

* In the process of decomposing the fractional part of the given differential neither the integral sign nor dx enters.

Case II. When the factors of the denominator are all of the first degree and some are repeated.

To every n -fold linear factor, such as $(x - a)^n$, there will correspond the sum of n partial fractions,

$$\frac{A}{(x - a)^n} + \frac{B}{(x - a)^{n-1}} + \cdots + \frac{L}{x - a},$$

in which A, B, \dots, L are constants. These partial fractions are readily integrated. For example,

$$\int \frac{A \, dx}{(x - a)^n} = A \int (x - a)^{-n} \, dx = \frac{A}{(1 - n)(x - a)^{n-1}} + C.$$

ILLUSTRATIVE EXAMPLE. Find $\int \frac{x^3 + 1}{x(x - 1)^3} \, dx$.

Solution. Since $x - 1$ occurs three times as a factor, we assume

$$\frac{x^3 + 1}{x(x - 1)^3} = \frac{A}{x} + \frac{B}{(x - 1)^3} + \frac{C}{(x - 1)^2} + \frac{D}{x - 1}.$$

Clearing of fractions,

$$x^3 + 1 = A(x - 1)^3 + Bx + Cx(x - 1) + Dx(x - 1)^2.$$

$$x^3 + 1 = (A + D)x^3 + (-3A + C + 2D)x^2 + (3A + B - C + D)x - A.$$

Equating the coefficients of like powers of x , we get the simultaneous equations

$$\begin{aligned} A + D &= 1, \\ -3A + C + 2D &= 0, \\ 3A + B - C + D &= 0, \\ -A &= 1. \end{aligned}$$

Solving, $A = -1, B = 2, C = 1, D = 2$, and

$$\frac{x^3 + 1}{x(x - 1)^3} = -\frac{1}{x} + \frac{2}{(x - 1)^3} + \frac{1}{(x - 1)^2} + \frac{2}{x - 1}.$$

$$\therefore \int \frac{x^3 + 1}{x(x - 1)^3} \, dx = -\ln x - \frac{1}{(x - 1)^2} - \frac{1}{x - 1} + 2 \ln (x - 1) + C$$

$$= -\frac{x}{(x - 1)^2} + \ln \frac{(x - 1)^2}{x} + C. \text{ Ans.}$$

PROBLEMS

Work out the following integrals.

$$1. \int \frac{(4x - 2)dx}{x^3 - x^2 - 2x} = \ln \frac{x^2 - 2x}{(x + 1)^2} + C.$$

$$2. \int \frac{(5x^2 - 3)dx}{x^3 - x} = \ln x^3(x^2 - 1) + C.$$

$$3. \int \frac{(4x + 3)dx}{4x^3 + 8x^2 + 3x} = \frac{1}{2} \ln \frac{x^2}{(2x + 1)(2x + 3)} + C.$$

$$4. \int \frac{(4x^3 + 2x^2 + 1)dx}{4x^3 - x} = x + \frac{1}{2} \ln \frac{(2x+1)(2x-1)^2}{x^2} + C.$$

$$5. \int \frac{(3x^2 + 5x)dx}{(x-1)(x+1)^2} = \ln(x+1)(x-1)^2 - \frac{1}{x+1} + C.$$

$$6. \int \frac{z^2 dz}{(z-1)^3} = \ln(z-1) - \frac{2}{z-1} - \frac{1}{2(z-1)^2} + C.$$

$$7. \int \frac{(y^4 - 8)dy}{y^3 + 2y^2} = \frac{y^2}{2} - 2y - \frac{4}{y} + 2 \ln(y^2 + 2y) + C.$$

$$8. \int_1^2 \frac{(x-3)dx}{x^3 + x^2} = 4 \ln \frac{4}{3} - \frac{3}{2} = -0.3492.$$

$$9. \int_2^4 \frac{(x^3 - 2)dx}{x^3 - x^2} = \frac{5}{2} + \ln \frac{4}{3} = 2.7877.$$

$$10. \int_1^3 \frac{(2-x^2)dx}{x^3 + 3x^2 + 2x} = \ln \frac{9}{10} = -0.1054.$$

$$11. \int_2^3 \frac{(3-x)dx}{x^3 + 4x^2 + 3x} = \ln \frac{81}{80} = 0.0125.$$

$$12. \int_0^1 \frac{(3x^2 + 7x)dx}{(x+1)(x+2)(x+3)} = \ln \frac{4}{3} = 0.2877.$$

$$13. \int_0^5 \frac{(x^2 - 3)dx}{(x+2)(x+1)^2} = \ln \frac{7}{2} - \frac{5}{3} = -0.4139.$$

$$14. \int_0^4 \frac{9x^2 dx}{(2x+1)(x+2)^2} = 5 \ln 3 - 4 = 1.4930.$$

Work out each of the following integrals.

$$15. \int \frac{8 dx}{x^3 - 4x}.$$

$$22. \int \frac{(5x^2 + 14x + 10)dx}{(x+2)(x+1)^2}.$$

$$16. \int \frac{(5x^2 - 9)dx}{x^3 - 9x}.$$

$$23. \int \frac{(24y^2 + 10y + 5)dy}{(2y-1)(2y+1)^2}.$$

$$17. \int \frac{(3z+7)dz}{(z+1)(z+2)(z+3)}.$$

$$24. \int \frac{(x+2)dx}{x^4 + 2x^3 + x^2}.$$

$$18. \int \frac{(3x^2 + 11x + 2)dx}{(x+3)(x^2-1)}.$$

$$25. \int \frac{(x^3 - 2x - 4)dx}{x^4 + 2x^3}.$$

$$19. \int \frac{x^2 dx}{(2x+3)(4x^2-1)}.$$

$$26. \int \frac{(2x^2 + 1)dx}{(x-2)^3}.$$

$$20. \int \frac{(t^4 + 1)dt}{t^3 - t}.$$

$$27. \int \frac{(y^4 - 3y^3)dy}{(y^2-1)(y-2)}.$$

$$21. \int \frac{(x^2 - x - 5)dx}{x^3 + 5x^2}.$$

$$28. \int \frac{(2t^4 + 3t^3 - 20t - 28)dt}{(t^2-4)(2t-1)}.$$

Case III. When the denominator contains factors of the second degree but none are repeated.

To every nonrepeated quadratic factor, such as $x^2 + px + q$, there corresponds a partial fraction of the form

$$\frac{Ax + B}{x^2 + px + q}.$$

The method of integration of this term is explained on page 209 (Illustrative Example 2).

If p is not zero, we complete the square in the denominator,

$$x^2 + px + \frac{1}{4}p^2 + q - \frac{1}{4}p^2 = (x + \frac{1}{2}p)^2 + \frac{1}{4}(4q - p^2). \quad (4q > p^2)$$

Let $x + \frac{1}{2}p = u$. Then $x = u - \frac{1}{2}p$, $dx = du$. Substituting these values, the new integral in terms of the variable u is readily integrated.

ILLUSTRATIVE EXAMPLE 1. Find $\int \frac{4 dx}{x^3 + 4x}$.

Solution. Assume $\frac{4}{x(x^2 + 4)} = \frac{A}{x} + \frac{Bx + C}{x^2 + 4}$.

Clearing of fractions, $4 = A(x^2 + 4) + x(Bx + C) = (A + B)x^2 + (C + 4A)x$. Equating the coefficients of like powers of x , we get

$$A + B = 0, \quad C = 0, \quad 4A = 4.$$

This gives $A = 1$, $B = -1$, $C = 0$, so that $\frac{4}{x(x^2 + 4)} = \frac{1}{x} - \frac{x}{x^2 + 4}$.

$$\begin{aligned} \therefore \int \frac{4 dx}{x(x^2 + 4)} &= \int \frac{dx}{x} - \int \frac{x dx}{x^2 + 4} \\ &= \ln x - \frac{1}{2} \ln (x^2 + 4) + \ln c = \ln \frac{cx}{\sqrt{x^2 + 4}}. \quad \text{Ans.} \end{aligned}$$

ILLUSTRATIVE EXAMPLE 2. Prove

$$\int \frac{dx}{x^3 + 8} = \frac{1}{24} \ln \frac{(x+2)^2}{x^2 - 2x + 4} + \frac{1}{12} \sqrt{3} \arctan \frac{x-1}{\sqrt{3}} + C.$$

Solution. Factoring, $x^3 + 8 = (x + 2)(x^2 - 2x + 4)$.

$$\frac{1}{x^3 + 8} = \frac{Ax + B}{x^2 - 2x + 4} + \frac{C}{x + 2},$$

$$1 = (Ax + B)(x + 2) + C(x^2 - 2x + 4),$$

$$1 = (A + C)x^2 + (2A + B - 2C)x + 2B + 4C.$$

Then $A = -\frac{1}{12}$, $B = \frac{1}{3}$, $C = \frac{1}{12}$.

$$\begin{aligned} \text{Hence} \quad \int \frac{dx}{x^3 + 8} &= \int \frac{-\frac{1}{12}x + \frac{1}{3}}{x^2 - 2x + 4} dx + \int \frac{\frac{1}{12} dx}{x + 2} \\ (4) \quad &= \frac{1}{12} \int \frac{4 - x}{x^2 - 2x + 4} dx + \frac{1}{12} \ln (x + 2) + C. \end{aligned}$$

Now $x^2 - 2x + 4 = (x - 1)^2 + 3 = u^2 + 3$, if $x - 1 = u$.

Then $x = u + 1$, $dx = du$, and

$$\int \frac{4 - x}{x^2 - 2x + 4} dx = \int \frac{3 - u}{u^2 + 3} du = \sqrt{3} \arctan \frac{u}{\sqrt{3}} - \frac{1}{2} \ln (u^2 + 3).$$

Substituting back $u = x - 1$, using (4), and reducing, we have the answer.

Case IV. When the denominator contains factors of the second degree some of which are repeated.

To every n -fold quadratic factor, such as $(x^2 + px + q)^n$, there will correspond the sum of n partial fractions,

$$\frac{Ax + B}{(x^2 + px + q)^n} + \frac{Cx + D}{(x^2 + px + q)^{n-1}} + \cdots + \frac{Lx + M}{x^2 + px + q}.$$

To carry out the integration, the "reduction formula"

$$(5) \quad \int \frac{du}{(u^2 + a^2)^n} = \frac{1}{2(n-1)a^2} \left[\frac{u}{(u^2 + a^2)^{n-1}} + (2n-3) \int \frac{du}{(u^2 + a^2)^{n-1}} \right],$$

proved in the next chapter, is necessary. If $n > 2$, repeated applications of (5) are necessary. If p is not zero, we complete the square,

$$x^2 + px + q = (x + \frac{1}{2}p)^2 + \frac{1}{4}(4q - p^2) = u^2 + a^2, \text{ etc., as before.}$$

ILLUSTRATIVE EXAMPLE. Prove

$$\int \frac{2x^3 + x + 3}{(x^2 + 1)^2} dx = \ln(x^2 + 1) + \frac{1 + 3x}{2(x^2 + 1)} + \frac{3}{2} \arctan x + C.$$

Solution. Since $x^2 + 1$ occurs twice as a factor, we assume

$$\frac{2x^3 + x + 3}{(x^2 + 1)^2} = \frac{Ax + B}{(x^2 + 1)^2} + \frac{Cx + D}{x^2 + 1}.$$

Clearing of fractions,

$$2x^3 + x + 3 = Ax + B + (Cx + D)(x^2 + 1).$$

Equating the coefficients of like powers of x and solving, we get

$$A = -1, \quad B = 3, \quad C = 2, \quad D = 0.$$

Hence

$$\begin{aligned} \int \frac{2x^3 + x + 3}{(x^2 + 1)^2} dx &= \int \frac{-x + 3}{(x^2 + 1)^2} dx + \int \frac{2x dx}{x^2 + 1} \\ &= \ln(x^2 + 1) - \int \frac{x dx}{(x^2 + 1)^2} + 3 \int \frac{dx}{(x^2 + 1)^2}. \end{aligned}$$

The first of these two integrals is worked out by the power formula (4), the second by (5) above, with $u = x$, $a = 1$, $n = 2$. Thus we obtain

$$\int \frac{2x^3 + x + 3}{(x^2 + 1)^2} dx = \ln(x^2 + 1) + \frac{1}{2(x^2 + 1)} + \frac{3}{2} \left[\frac{x}{x^2 + 1} + \arctan x \right] + C.$$

Reducing, we have the answer.

Conclusion. Since a rational function may always be reduced to the quotient of two integral rational functions, that is, to a rational fraction, it follows from the above discussion that any rational function whose denominator can be broken up into real quadratic and linear factors may be expressed as the algebraic sum of integral rational functions and partial fractions. The terms of this sum have forms all of which we have shown how to integrate. Hence the

Theorem. *The integral of every rational function whose denominator can be broken up into real quadratic and linear factors may be found, and is expressible in terms of algebraic, logarithmic, and inverse trigonometric functions, that is, in terms of the elementary functions.*

PROBLEMS

Work out the following integrals.

1. $\int \frac{(4x^2 + 6)dx}{x^3 + 3x} = \ln x^2(x^2 + 3) + C.$
2. $\int \frac{(x^2 + x)dx}{(x - 1)(x^2 + 1)} = \ln(x - 1) + \arctan x + C.$
3. $\int \frac{(2t^2 - 8t - 8)dt}{(t - 2)(t^2 + 2)} = 2 \ln \frac{t^2 + 4}{t - 2} + C.$
4. $\int \frac{(x^2 + x - 10)dx}{(2x - 3)(x^2 + 4)} = \frac{1}{2} \ln \frac{x^2 + 4}{2x - 3} + \arctan \frac{x}{2} + C.$
5. $\int \frac{(x - 18)dx}{4x^3 + 9x} = \ln \frac{4x^2 + 9}{x^2} + \frac{1}{6} \arctan \frac{2x}{3} + C.$
6. $\int \frac{(2y^3 + y^2 + 2y + 2)dy}{y^4 + 3y^2 + 2} = \ln(y^2 + 2) + \arctan y + C.$
7. $\int \frac{dz}{z^4 + z^2} = -\frac{1}{z} - \arctan z + C.$
8. $\int \frac{2x dx}{(x^2 + 1)(x + 1)^2} = \arctan x + \frac{1}{x + 1} + C.$
9. $\int \frac{(x^3 + 3x)dx}{(x^2 + 1)^2} = \frac{1}{2} \ln(x^2 + 1) - \frac{1}{x^2 + 1} + C.$
10. $\int \frac{(x^5 + 9x^3 - 9x^2 - 9)dx}{x^3 + 9x} = \frac{x^3}{3} - \ln x(x^2 + 9)^4 + C.$
11. $\int \frac{(4x^2 + 2x + 8)dx}{x(x^2 + 2)^2} = \ln \frac{x^2}{x^2 + 2} + \frac{x}{2x^2 + 4} + \frac{\sqrt{2}}{4} \arctan \frac{x}{\sqrt{2}} + C.$
12. $\int \frac{t^5 dt}{(t^2 + 4)^2} = \frac{t^2}{2} - 4 \ln(t^2 + 4) - \frac{8}{t^2 + 4} + C.$
13. $\int \frac{dx}{x^3 + x^2 + x} = -\frac{1}{2} \ln \frac{x^2 + x + 1}{x^2} - \frac{\sqrt{3}}{3} \arctan \frac{2x + 1}{\sqrt{3}} + C.$
14. $\int \frac{(x^5 + 4x^3)dx}{(x^2 + 2)^3} = \frac{1}{2} \ln(x^2 + 2) + \frac{1}{(x^2 + 2)^2} + C.$
15. $\int \frac{4 dx}{x^4 - 1} = \ln \frac{x - 1}{x + 1} - 2 \arctan x + C.$
16. $\int \frac{(2z^2 + 3z + 2)dz}{(z + 2)(z^2 + 2z + 2)} = 2 \ln(z + 2) - \arctan(z + 1) + C.$

$$17. \int \left(\frac{t+3}{t^2+4t+5} \right)^2 dt = \arctan(t+2) - \frac{1}{t^2+4t+5} + C.$$

$$18. \int_1^4 \frac{(5x^2+4)dx}{x^3+4x} = 3 \ln 4 = 4.1589.$$

$$19. \int_0^1 \frac{5x dx}{(x+2)(x^2+1)} = \ln \frac{8}{9} + \frac{\pi}{4} = 0.667.$$

$$20. \int_0^1 \frac{(2x^2+x+3)dx}{(x+1)(x^2+1)} = \ln 4 + \frac{\pi}{4} = 2.171.$$

$$21. \int_0^1 \frac{(4x^2+2x)dx}{(x^2+1)(x+1)^2} = \frac{\pi}{4} + \frac{1}{2} - \ln 2 = 0.592.$$

$$22. \int_1^4 \frac{(5t^3-4t)dt}{t^4-16} = \ln \frac{12}{5} + \frac{3}{2} \ln \frac{20}{13} = 1.522.$$

$$23. \int_0^2 \frac{(z^3+2z^2+6z+8)dz}{(z^2+4)^2} = \frac{1}{2} \ln 2 + \frac{\pi}{4} + \frac{1}{8} = 1.257.$$

Work out each of the following integrals.

$$24. \int \frac{(6x^2+3x+4)dx}{x^3+2x}.$$

$$29. \int \frac{(4x^3+3x^2+18x+12)dx}{(x^2+4)^2}.$$

$$25. \int \frac{(z^4+3)dz}{(z+1)(z^2+1)}.$$

$$30. \int_0^{\frac{1}{2}} \frac{8y dy}{(2y+1)(4y^2+1)}.$$

$$26. \int \frac{(3x^3+3x+1)dx}{x^4+3x^2}.$$

$$31. \int_0^1 \frac{(2x^3-4)dx}{(x^2+1)(x+1)^2}.$$

$$27. \int \frac{(3x^3+x^2+3)dx}{x^4+3x^2}.$$

$$32. \int_1^3 \frac{(x+10)dx}{x^3+2x^2+5x}.$$

$$28. \int \frac{(5x^2+12x+9)dx}{x^3+3x^2+3x}.$$

$$33. \int_0^3 \frac{(2x^3+18)dx}{(x+3)(x^2+9)}.$$

168. Integration by substitution of a new variable; rationalization.

In the last article it was shown that all rational functions whose denominators can be broken up into real quadratic and linear factors may be integrated. Of algebraic functions which are *not rational*, that is, such as contain radicals, only a small number, relatively speaking, can be integrated in terms of elementary functions. By substituting a new variable, however, these functions can in some cases be transformed into equivalent functions that are either in the list of standard forms (Art. 128) or else rational. The method of integrating a function that is not rational by substituting for the old variable such a function of a new variable that the result is a rational function is sometimes called *integration by rationalization*. This is a very important artifice in integration, and we shall now take up some of the more important cases coming under this head.

Differentials containing fractional powers of x only. Such an expression can be transformed into a rational form by means of the substitution

$$x = z^n,$$

where n is the least common denominator of the fractional exponents of x .

For x , dx , and each radical can then be expressed rationally in terms of z .

ILLUSTRATIVE EXAMPLE 1. Prove $\int \frac{x^{\frac{1}{2}} dx}{1+x^{\frac{3}{4}}} = \frac{4}{3} x^{\frac{3}{4}} - \frac{4}{3} \ln(1+x^{\frac{3}{4}}) + C$.

Solution. Here $n = 4$. Hence let $x = z^4$.

Then $x^{\frac{1}{2}} = z^2$, $x^{\frac{3}{4}} = z^3$, $dx = 4 z^3 dz$.

$$\begin{aligned} \text{Then } \int \frac{x^{\frac{1}{2}} dx}{1+x^{\frac{3}{4}}} &= \int \frac{z^2}{1+z^3} 4 z^3 dz = 4 \int \frac{z^5}{1+z^3} dz \\ &= 4 \int \left(z^2 - \frac{z^2}{1+z^3} \right) dz = \frac{4}{3} z^3 - \frac{4}{3} \ln(1+z^3) + C. \end{aligned}$$

Substituting back $z = x^{\frac{1}{4}}$, we have the answer.

The general form of the irrational expression here treated is then

$$R\left(x^{\frac{1}{n}}\right)dx,$$

where R denotes a rational function of $x^{\frac{1}{n}}$.

Differentials containing fractional powers of $a + bx$ only. Such an expression can be transformed into a rational form by means of the substitution

$$a + bx = z^n,$$

where n is the least common denominator of the fractional exponents of the expression $a + bx$.

For x , dx , and each radical can then be expressed rationally in terms of z .

ILLUSTRATIVE EXAMPLE 2. Find $\int \frac{dx}{(1+x)^{\frac{3}{2}} + (1+x)^{\frac{1}{2}}}$.

Solution. Assume $1+x = z^2$.

Then $dx = 2z dz$, $(1+x)^{\frac{3}{2}} = z^3$, and $(1+x)^{\frac{1}{2}} = z$.

$$\begin{aligned} \therefore \int \frac{dx}{(1+x)^{\frac{3}{2}} + (1+x)^{\frac{1}{2}}} &= \int \frac{2z dz}{z^3 + z} = 2 \int \frac{dz}{z^2 + 1} \\ &= 2 \arctan z + C = 2 \arctan(1+x)^{\frac{1}{2}} + C \end{aligned}$$

when we substitute back the value of z in terms of x .

The general integral treated here has then the form

$$R\left[x, (a + bx)^{\frac{1}{n}}\right]dx,$$

where R denotes a rational function.

PROBLEMS

Work out the following integrals.

1. $\int \frac{(5x+9)dx}{(x-9)x^{\frac{3}{2}}} = \frac{2}{\sqrt{x}} + 2 \ln \frac{\sqrt{x}-3}{\sqrt{x}+3} + C.$
2. $\int \frac{\sqrt{x} dx}{x^3 + 2x^2 - 3x} = \frac{1}{4} \ln \frac{\sqrt{x}-1}{\sqrt{x}+1} - \frac{\sqrt{3}}{6} \arctan \sqrt{\frac{x}{3}} + C.$
3. $\int \frac{dx}{x-x^{\frac{1}{3}}} = 3 \ln \frac{x^{\frac{1}{3}}}{1-x^{\frac{1}{3}}} + C.$
4. $\int \frac{(x^{\frac{1}{2}} - x^{\frac{1}{3}})dx}{6x^{\frac{1}{4}}} = \frac{2}{27} x^{\frac{9}{4}} - \frac{2}{13} x^{\frac{13}{4}} + C.$
5. $\int \frac{x^2 dx}{(4x+1)^{\frac{3}{2}}} = \frac{6x^2 + 6x + 1}{12(4x+1)^{\frac{3}{2}}} + C.$
6. $\int \frac{dx}{x^{\frac{8}{3}} - x^{\frac{1}{3}}} = \frac{8x^{\frac{3}{8}}}{3} + 2 \ln \frac{x^{\frac{1}{8}} - 1}{x^{\frac{1}{8}} + 1} + 4 \arctan x^{\frac{1}{8}} + C.$
7. $\int \frac{x dx}{(a+bx)^{\frac{3}{2}}} = \frac{2(2a+bx)}{b^2 \sqrt{a+bx}} + C.$
8. $\int y \sqrt[3]{a+y} dy = \frac{3}{28} (4y-3a)(a+y)^{\frac{4}{3}} + C.$
9. $\int \frac{(\sqrt{x+1}+1)dx}{\sqrt{x+1}-1} = x+1 + 4\sqrt{x+1} + 4 \ln (\sqrt{x+1}-1) + C.$
10. $\int \frac{dx}{1 + \sqrt[3]{x+a}} = \frac{3}{2} (x+a)^{\frac{2}{3}} - 3(x+a)^{\frac{1}{3}} + 3 \ln (1 + \sqrt[3]{x+a}) + C.$
11. $\int \frac{(t+5)dt}{(t+4)\sqrt{t+2}} = 2\sqrt{t+2} + \sqrt{2} \arctan \sqrt{\frac{t+2}{2}} + C.$
12. $\int_0^3 \frac{dx}{(x+2)\sqrt{x+1}} = 2 \arctan 2 - \frac{\pi}{2}.$
13. $\int_0^4 \frac{dx}{1 + \sqrt{x}} = 4 - 2 \ln 3.$
14. $\int_1^4 \frac{y dy}{\sqrt{2+4y}} = \frac{3}{2} \sqrt{2}.$
15. $\int_0^{\frac{1}{3}} \frac{dt}{\sqrt{2}t(9 + \sqrt[3]{2}t)} = 3 - 9 \arctan \frac{1}{3}.$
16. $\int_0^1 \frac{x^{\frac{3}{2}} dx}{x+1} = \frac{\pi}{2} - \frac{4}{3}.$
17. $\int_1^{64} \frac{dt}{2\sqrt{t} + \sqrt[3]{t}} = 5.31.$
18. $\int_3^{29} \frac{(x-2)^{\frac{3}{2}} dx}{(x-2)^{\frac{3}{2}} + 3} = 8 + \frac{3}{2} \pi \sqrt{3}.$

Work out each of the following integrals.

$$19. \int \frac{dx}{x + 2\sqrt{x} + 5}.$$

$$23. \int \frac{dt}{(t+1)^{\frac{1}{4}} + (t+1)^{\frac{5}{4}}}.$$

$$20. \int \frac{dx}{x(1 - \sqrt[3]{x})}.$$

$$24. \int \frac{dx}{(x-2)^{\frac{1}{2}} - (x-2)^{\frac{3}{2}}}.$$

$$21. \int \frac{(x+2)dx}{x\sqrt{x-3}}.$$

$$25. \int \frac{(x+3)dx}{(x+5)\sqrt{x+4}}.$$

$$22. \int \frac{y dy}{(2y+3)^{\frac{4}{3}}}.$$

$$26. \int \frac{(2 - \sqrt{2x+3})dx}{1-2x}.$$

27. Find the area bounded by the curve $y = x + \sqrt{x+1}$, the x -axis, and the ordinates $x = 3$ and $x = 8$. Ans. $40\frac{1}{6}$.

28. Find the volume generated by revolving about the x -axis the area of the preceding problem.

29. Find the volume generated by revolving about the x -axis the area in the first quadrant bounded by the coordinate axes and each of the following curves.

(a) $y = 2 - \sqrt{x}$.

(c) $y = a - \sqrt{ax}$.

(b) $y = 2 - \sqrt[3]{x}$.

(d) $y = 4 - x^{\frac{2}{3}}$.

30. Find the area bounded by the curves $y = 2x + \sqrt{2x+1}$ and $y = x - \sqrt{2x+1}$ and the ordinates $x = 4$ and $x = 12$.

31. Find the area bounded by the curve

$$(x-1)y^2 = (x+1)(2y-1)$$

and the ordinates $x = 3$ and $x = 8$. Ans. $4 \left| \sqrt{2} + \ln \frac{4 + \sqrt{2}}{4 - \sqrt{2}} \right|$.

169. Binomial differentials. A differential of the form

$$(1) \quad x^m(a + bx^n)^p dx,$$

where a and b are any constants and the exponents m , n , p are rational numbers, is called a *binomial differential*.

Let $x = z^\alpha$; then $dx = \alpha z^{\alpha-1} dz$,

and $x^m(a + bx^n)^p dx = \alpha z^{m\alpha + \alpha - 1} (a + bz^{n\alpha})^p dz.$

If an integer α be chosen such that $m\alpha$ and $n\alpha$ are also integers,* we see that the given differential is equivalent to another of the same form where m and n have been replaced by integers. Also,

$$(2) \quad x^m(a + bx^n)^p dx = x^{m+n\alpha} (ax^{-n} + b)^p dx$$

* It is always possible to choose α so that $m\alpha$ and $n\alpha$ are integers, for we can take α as the L.C.M. of the denominators of m and n .

transforms the given differential into another of the same form where the exponent n of x has been replaced by $-n$. Therefore, no matter what the algebraic sign of n may be, in one of the two differentials the exponent of x inside the parentheses will surely be positive.

When p is a positive integer the binomial may be expanded and the differential integrated termwise. In what follows p is regarded as a fraction; hence we replace it by $\frac{r}{s}$, where r and s are integers.*

We may then make the following statement.

Every binomial differential may be reduced to the form

$$x^m(a + bx^n)^{\frac{r}{s}} dx,$$

where m, n, r, s are integers and n is positive.

In the next section we prove that (1) can be rationalized under the following conditions.

CASE I. When $\frac{m+1}{n} = \text{an integer or zero}$, by assuming
 $a + bx^n = z^n$.

CASE II. When $\frac{m+1}{n} + \frac{r}{s} = \text{an integer or zero}$, by assuming
 $a + bx^n = z^n x^n$.

$$\begin{aligned} \text{ILLUSTRATIVE EXAMPLE 1. } \int \frac{x^3 dx}{(a + bx^2)^{\frac{3}{2}}} &= \int x^3 (a + bx^2)^{-\frac{3}{2}} dx \\ &= \frac{1}{b^2} \frac{2a + bx^2}{\sqrt{a + bx^2}} + C. \end{aligned}$$

Solution. $m = 3, n = 2, r = -3, s = 2$; and here $\frac{m+1}{n} = 2$, an integer. Hence this comes under Case I, and we assume

$$a + bx^2 = z^2; \text{ whence } x = \left(\frac{z^2 - a}{b} \right)^{\frac{1}{2}}, dx = \frac{z dz}{b^{\frac{1}{2}} (z^2 - a)^{\frac{1}{2}}}, \text{ and } (a + bx^2)^{\frac{3}{2}} = z^3.$$

$$\begin{aligned} \therefore \int \frac{x^3 dx}{(a + bx^2)^{\frac{3}{2}}} &= \int \left(\frac{z^2 - a}{b} \right)^{\frac{1}{2}} \cdot \frac{z dz}{b^{\frac{1}{2}} (z^2 - a)^{\frac{1}{2}}} \cdot \frac{1}{z^3} \\ &= \frac{1}{b^2} \int (1 - az^{-2}) dz = \frac{1}{b^2} (z + az^{-1}) + C \\ &= \frac{1}{b^2} \frac{2a + bx^2}{\sqrt{a + bx^2}} + C. \end{aligned}$$

$$\text{ILLUSTRATIVE EXAMPLE 2. } \int \frac{dx}{x^4 \sqrt{1 + x^2}} = \frac{(2x^2 - 1)(1 + x^2)^{\frac{1}{2}}}{3x^3} + C.$$

Solution. $m = -4, n = 2, \frac{r}{s} = -\frac{1}{2}$; and here $\frac{m+1}{n} + \frac{r}{s} = -2$, an integer.

* The case where p is an integer is not excluded, but appears as a special case, namely, $r = p, s = 1$.

Hence this comes under Case II, and we assume

$$1 + x^2 = z^2 x^2, \quad z = \frac{(1 + x^2)^{\frac{1}{2}}}{x};$$

whence $x^2 = \frac{1}{z^2 - 1}, \quad 1 + x^2 = \frac{z^2}{z^2 - 1}, \quad \sqrt{1 + x^2} = \frac{z}{(z^2 - 1)^{\frac{1}{2}}};$

also $x = \frac{1}{(z^2 - 1)^{\frac{1}{2}}}, \quad x^3 = \frac{1}{(z^2 - 1)^{\frac{3}{2}}}; \quad \text{and} \quad dx = -\frac{z dz}{(z^2 - 1)^{\frac{3}{2}}}.$

$$\begin{aligned} \therefore \int \frac{dx}{x^4 \sqrt{1 + x^2}} &= - \int \frac{\frac{z dz}{(z^2 - 1)^{\frac{3}{2}}}}{\frac{1}{(z^2 - 1)^2} \cdot \frac{z}{(z^2 - 1)^{\frac{1}{2}}}} = - \int (z^2 - 1) dz \\ &= z - \frac{z^3}{3} + C = \frac{(2x^2 - 1)(1 + x^2)^{\frac{1}{2}}}{3x^3} + C. \end{aligned}$$

PROBLEMS

Work out the following integrals.

$$1. \int x^5 \sqrt{1 + x^3} dx = \frac{2(3x^3 - 2)(1 + x^3)^{\frac{3}{2}}}{45} + C.$$

$$2. \int \frac{x^5 dx}{\sqrt{1 + x^3}} = \frac{2(x^3 - 2)\sqrt{1 + x^3}}{9} + C.$$

$$3. \int x^5 (8 + x^3)^{\frac{3}{2}} dx = \frac{2(5x^3 - 16)(8 + x^3)^{\frac{5}{2}}}{105} + C.$$

$$4. \int \frac{x^5 dx}{(a + bx^3)^{\frac{1}{2}}} = \frac{2(2a + bx^3)}{3b^2 \sqrt{a + bx^3}} + C.$$

$$5. \int \frac{dx}{x^2(1 + x^3)^{\frac{3}{2}}} = -\frac{(1 + x^3)^{\frac{1}{2}}}{x} + C.$$

$$6. \int \frac{dx}{x^3(1 + x^3)^{\frac{3}{2}}} = -\frac{(1 + x^3)^{\frac{1}{2}}}{2x^2} + C.$$

$$7. \int \frac{dx}{x^2(1 + x^4)^{\frac{3}{2}}} = -\frac{(1 + x^4)^{\frac{1}{2}}}{x} + C.$$

$$8. \int \frac{dx}{x^n(1 + x^n)^{\frac{1}{n}}} = -\frac{(1 + x^n)^{\frac{n-1}{n}}}{(n-1)x^{n-1}} + C.$$

$$9. \int \frac{dx}{x^3(1 + x^3)^{\frac{4}{3}}} = -\frac{1 + 3x^3}{2x^2(1 + x^3)^{\frac{1}{3}}} + C.$$

$$10. \int \frac{2\sqrt{1 + x^4} dx}{x^3} = \ln(x^2 + \sqrt{1 + x^4}) - \frac{\sqrt{1 + x^4}}{x^2} + C.$$

Work out each of the following integrals.

$$11. \int x^5 \sqrt{1-x^3} dx. \quad 12. \int \frac{x^5 dx}{\sqrt{a+bx^3}}. \quad 13. \int x^5 (a^3 - x^3)^{\frac{1}{2}} dx.$$

$$14. \int \frac{(x^5 + 2x^2) dx}{(1+x^3)^{\frac{3}{2}}}. \quad 15. \int x(1+x^3)^{\frac{1}{2}} dx.$$

170. Conditions of rationalization of the binomial differential

$$(A) \quad x^m (a + bx^n)^{\frac{r}{s}} dx.$$

CASE I. Assume $a + bx^n = z^s$.

$$\text{Then} \quad (a + bx^n)^{\frac{1}{s}} = z, \quad \text{and} \quad (a + bx^n)^{\frac{r}{s}} = z^r;$$

$$\text{also} \quad x = \left(\frac{z^s - a}{b} \right)^{\frac{1}{n}}, \quad \text{and} \quad x^m = \left(\frac{z^s - a}{b} \right)^{\frac{m}{n}};$$

$$\text{hence} \quad dx = \frac{s}{bn} z^{s-1} \left(\frac{z^s - a}{b} \right)^{\frac{1}{n}-1} dz.$$

Substituting in (A), we get

$$x^m (a + bx^n)^{\frac{r}{s}} dx = \frac{s}{bn} z^{r+s-1} \left(\frac{z^s - a}{b} \right)^{\frac{m}{n} + 1 - 1} dz.$$

The second member of this expression is rational when

$$\frac{m+1}{n}$$

is an integer or zero.

CASE II. Assume $a + bx^n = z^s x^n$.

$$\text{Then} \quad x^n = \frac{a}{z^s - b}, \quad \text{and} \quad a + bx^n = z^s x^n = \frac{az^s}{z^s - b}.$$

$$\text{Hence} \quad (a + bx^n)^{\frac{r}{s}} = a^{\frac{r}{s}} (z^s - b)^{-\frac{r}{s}} z^r;$$

$$\text{also} \quad x = a^{\frac{1}{n}} (z^s - b)^{-\frac{1}{n}}, \quad x^m = a^{\frac{m}{n}} (z^s - b)^{-\frac{m}{n}};$$

$$\text{and} \quad dx = -\frac{s}{n} a^{\frac{1}{n}} z^{s-1} (z^s - b)^{-\frac{1}{n}-1} dz.$$

Substituting in (A), we get

$$x^m (a + bx^n)^{\frac{r}{s}} dx = -\frac{s}{n} a^{\frac{m}{n} + \frac{1}{s} + \frac{r}{s}} (z^s - b)^{-\left(\frac{m+1}{n} + \frac{r}{s} + 1\right)} z^{r+s-1} dz.$$

The second member of this expression is rational when $\frac{m+1}{n} + \frac{r}{s}$ is an integer or zero.

Hence the binomial differential

$$x^m(a + bx^n)^{\frac{r}{s}} dx$$

can be rationalized in the cases given in the preceding article.

171. Transformation of trigonometric differentials.

Theorem. *A trigonometric differential involving $\sin u$ and $\cos u$ rationally only can be transformed by means of the substitution*

$$(1) \quad \tan \frac{u}{2} = z,$$

or, what is the same thing, by the substitutions

$$(2) \quad \sin u = \frac{2z}{1+z^2}, \quad \cos u = \frac{1-z^2}{1+z^2}, \quad du = \frac{2dz}{1+z^2}$$

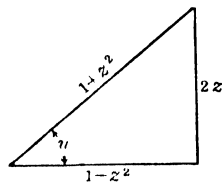
into another differential expression which is rational in z .

Proof. From the formula for the tangent of half an angle in (5), Art. 2, after squaring both members, we have

$$\tan^2 \frac{1}{2} u = \frac{1 - \cos u}{1 + \cos u}.$$

Substituting $\tan \frac{1}{2} u = z$, and solving for $\cos u$,

$$(3) \quad \cos u = \frac{1 - z^2}{1 + z^2},$$



one of the formulas (2). The right triangle in the figure shows the relation (3) and gives also $\sin u$ as in (2). Finally, from (1),

$$u = 2 \arctan z,$$

and hence

$$du = \frac{2dz}{1+z^2}.$$

Thus the relations (2) are proved.

It is evident that if a trigonometric differential involves $\tan u$, $\cot u$, $\sec u$, $\csc u$ rationally only, it will be included in the above theorem, since these four functions can be expressed rationally in terms of $\sin u$, or $\cos u$, or both. It follows, therefore, that *any rational trigonometric differential can be integrated, provided the transformed differential in terms of z can be separated into partial fractions* (see Art. 167).

ILLUSTRATIVE EXAMPLE. Prove $\int \frac{dx}{5+4\sin 2x} = \frac{1}{3} \operatorname{arc tan} \left(\frac{5 \tan x + 4}{3} \right) + C$.

Solution. Let $2x = u$. Then $x = \frac{1}{2}u$, $dx = \frac{1}{2}du$. Substituting these values, and then using (2), we have

$$\begin{aligned} \int \frac{dx}{5+4\sin 2x} &= \frac{1}{2} \int \frac{du}{5+4\sin u} = \frac{1}{2} \int \frac{\frac{2dz}{1+z^2}}{5+\frac{8z}{1+z^2}} = \int \frac{dz}{5z^2+8z+5} \\ &= \frac{1}{3} \operatorname{arc tan} \left(\frac{5z+4}{3} \right) + C. \end{aligned}$$

Substituting back $z = \tan \frac{1}{2}u = \tan x$ gives the above result.

PROBLEMS

Work out the following integrals.

1. $\int \frac{d\theta}{1 + \sin \theta + \cos \theta} = \ln \left(1 + \tan \frac{\theta}{2} \right) + C.$
2. $\int \frac{dx}{\sin x + \tan x} = \frac{1}{2} \ln \tan \frac{x}{2} - \frac{1}{4} \tan^2 \frac{x}{2} + C.$
3. $\int \frac{d\phi}{5+4\cos \phi} = \frac{2}{3} \operatorname{arc tan} \left(\frac{1}{3} \tan \frac{\phi}{2} \right) + C.$
4. $\int \frac{dx}{4+5\cos x} = \frac{1}{3} \ln \left(\frac{\tan \frac{x}{2} + 3}{\tan \frac{x}{2} - 3} \right) + C.$
5. $\int \frac{d\alpha}{3+\cos \alpha} = \frac{1}{\sqrt{2}} \operatorname{arc tan} \left(\frac{1}{\sqrt{2}} \tan \frac{\alpha}{2} \right) + C.$
6. $\int \frac{dx}{2\sin x - \cos x + 3} = \operatorname{arc tan} \left(1 + 2 \tan \frac{x}{2} \right) + C.$
7. $\int \frac{\cos \theta d\theta}{5-3\cos \theta} = -\frac{\theta}{3} + \frac{5}{6} \operatorname{arc tan} \left(2 \tan \frac{\theta}{2} \right) + C.$
8. $\int \frac{dx}{4\sec x + 5} = \frac{2}{5} \operatorname{arc tan} \left(\tan \frac{x}{2} \right) + \frac{4}{15} \ln \left(\frac{\tan \frac{x}{2} - 3}{\tan \frac{x}{2} + 3} \right) + C.$
9. $\int_0^{\pi} \frac{d\theta}{4-3\cos \theta} = \frac{\pi}{\sqrt{7}}.$
10. $\int_0^{\frac{\pi}{2}} \frac{d\phi}{12+13\cos \phi} = \frac{1}{7} \ln \frac{3}{2}.$
11. $\int_0^{\frac{\pi}{2}} \frac{dx}{2+\sin x} = \frac{\pi}{3\sqrt{3}}.$
12. $\int_0^{\frac{\pi}{2}} \frac{d\alpha}{3+5\sin \alpha} = \frac{1}{4} \ln 3.$

Work out each of the following integrals

$$13. \int \frac{dx}{1 + \sin x - \cos x}.$$

$$16. \int \frac{dt}{13 \cos t - 5}.$$

$$14. \int \frac{d\theta}{\cot \theta + \csc \theta}.$$

$$17. \int \frac{dx}{2 \cos x + 1}.$$

$$15. \int \frac{d\phi}{13 - 5 \cos \phi}.$$

$$18. \int \frac{d\alpha}{2 + \sin \alpha}.$$

$$19. \int \frac{dx}{1 + 2 \sin x}.$$

$$21. \int \frac{dt}{5 \sec t - 4}.$$

$$23. \int_0^{\pi} \frac{d\theta}{3 + 2 \cos \theta}.$$

$$20. \int \frac{\sin \theta d\theta}{5 + 4 \sin \theta}.$$

$$22. \int_0^{2\pi} \frac{dx}{5 + 3 \cos x}.$$

$$24. \int_0^{\frac{\pi}{2}} \frac{d\alpha}{2 + \cos \alpha}.$$

172. Miscellaneous substitutions. So far the substitutions considered have rationalized the given differential expression. In a great number of cases, however, integrations may be effected by means of substitutions which do not rationalize the given differential, but no general rule can be given, and the experience gained in working out a large number of problems must be our guide.

A very useful substitution is

$$x = \frac{1}{z}, \quad dx = -\frac{dz}{z^2},$$

called the **reciprocal substitution**. Let us use this substitution in the next example.

ILLUSTRATIVE EXAMPLE. Find $\int \frac{\sqrt{a^2 - x^2}}{x^4} dx$.

Solution. Making the substitution $x = \frac{1}{z}$, $dx = -\frac{dz}{z^2}$, we get

$$\int \frac{\sqrt{a^2 - x^2}}{x^4} dx = -\int (a^2 z^2 - 1)^{\frac{1}{2}} z dz = -\frac{(a^2 z^2 - 1)^{\frac{3}{2}}}{\frac{3}{2} a^2} + C = -\frac{(a^2 - x^2)^{\frac{3}{2}}}{\frac{3}{2} a^2 x^3} + C.$$

PROBLEMS

Work out the following integrals.

$$1. \int \frac{dx}{x\sqrt{1+x+x^2}} = \ln \left(\frac{cx}{2+x+2\sqrt{1+x+x^2}} \right). \quad \text{Let } x = \frac{1}{z}.$$

$$2. \int \frac{dx}{x\sqrt{x^2-x+2}} = \frac{1}{\sqrt{2}} \ln \left(\frac{\sqrt{x^2-x+2}+x-\sqrt{2}}{\sqrt{x^2-x+2}+x+\sqrt{2}} \right) + C.$$

$$\text{Let } \sqrt{x^2-x+2} = z-x.$$

$$3. \int \frac{dx}{x\sqrt{x^2+2x-1}} = 2 \arctan (x + \sqrt{x^2+2x-1}) + C.$$

$$\text{Let } \sqrt{x^2+2x-1} = z-x.$$

$$4. \int \frac{dx}{x\sqrt{2+x-x^2}} = \frac{1}{\sqrt{2}} \ln \left(\frac{\sqrt{2+2x}-\sqrt{2-x}}{\sqrt{2+2x}+\sqrt{2-x}} \right) + C.$$

$$\text{Let } \sqrt{2+x-x^2} = (x+1)z.$$

$$5. \int \frac{dx}{x\sqrt{5x-6-x^2}} = -\sqrt{\frac{2}{3}} \arctan \sqrt{\frac{2(3-x)}{3(x-2)}} + C.$$

$$\text{Let } \sqrt{5x-6-x^2} = (x-2)z.$$

$$6. \int \frac{dx}{x\sqrt{3x^2-2x-1}} = -\arcsin \left(\frac{1+x}{2x} \right) + C. \quad \text{Let } x = \frac{1}{z}.$$

$$7. \int \frac{-dx}{x\sqrt{1+4x+5x^2}} = \ln \left(\frac{1+2x+\sqrt{1+4x+5x^2}}{x} \right) + C. \quad \text{Let } x = \frac{1}{z}.$$

$$8. \int \frac{dx}{x\sqrt{x^2+4x-4}} = -\frac{1}{2} \arcsin \left(\frac{2-x}{x\sqrt{2}} \right) + C. \quad \text{Let } x = \frac{1}{z}.$$

$$9. \int \frac{dx}{x^2\sqrt{1+2x+3x^2}} = -\frac{\sqrt{1+2x+3x^2}}{x} + \ln \left(\frac{1+x+\sqrt{1+2x+3x^2}}{x} \right) + C.$$

$$\text{Let } x = \frac{1}{z}.$$

$$10. \int \frac{dx}{x^2\sqrt{27x^2+6x-1}} = \frac{\sqrt{27x^2+6x-1}}{x} - 3 \arcsin \left(\frac{1-3x}{6x} \right) + C. \quad \text{Let } x = \frac{1}{z}.$$

$$11. \int_1^{\frac{1}{3}} \frac{(x-x^3)^{\frac{1}{3}} dx}{x^4} = 6. \quad \text{Let } x = \frac{1}{z}.$$

$$12. \int_0^1 \frac{dx}{e^x + e^{-x}} = \arctan e - \frac{\pi}{4}. \quad \text{Let } e^x = z.$$

$$13. \int_0^a \frac{dx}{\sqrt{ax-x^2}} = \pi. \quad \text{Let } x = a \sin^2 z.$$

$$14. \int_0^1 \sqrt{2t+t^2} dt = \sqrt{3} - \frac{1}{2} \ln(2+\sqrt{3}). \quad \text{Let } t+1 = z.$$

Work out each of the following integrals.

$$15. \int \frac{4 dx}{x\sqrt{x^2-2x+3}}. \quad \text{Let } \sqrt{x^2-2x+3} = z-x.$$

$$16. \int \frac{4 x dx}{(x^2-2x+3)^{\frac{3}{2}}}. \quad \text{Let } \sqrt{x^2-2x+3} = z-x.$$

$$17. \int \frac{2 dx}{\sqrt{5x-6-x^2}}. \quad \text{Let } \sqrt{5x-6-x^2} = (x-2)z.$$

$$18. \int \frac{2 x dx}{\sqrt{5x-6-x^2}}. \quad \text{Let } \sqrt{5x-6-x^2} = (x-2)z$$

CHAPTER XVII

REDUCTION FORMULAS. USE OF TABLE OF INTEGRALS

173. Introduction. In this chapter formal integration is completed. The aim is eventually to lay down directions for using a table of integrals. Methods of deriving certain general formulas, called *reduction formulas*, given in all tables are developed, since these methods are typical in problems of this sort.

174. Reduction formulas for binomial differentials. When the binomial differential cannot be integrated readily by any of the methods shown so far, it is customary to employ reduction formulas deduced by the method of integration by parts. By means of these reduction formulas the given differential is expressed as the sum of two terms, one of them not affected by the sign of integration, and the other an integral of the same form as the original expression, but one which is easier to integrate. The following are the four principal reduction formulas.

$$(A) \int x^m (a + bx^n)^p dx = \frac{x^{m-n+1} (a + bx^n)^{p+1}}{(np + m + 1)b} - \frac{(m - n + 1)a}{(np + m + 1)b} \int x^{m-n} (a + bx^n)^p dx.$$

$$(B) \int x^m (a + bx^n)^p dx = \frac{x^{m+1} (a + bx^n)^p}{np + m + 1} + \frac{anp}{np + m + 1} \int x^m (a + bx^n)^{p-1} dx.$$

$$(C) \int x^m (a + bx^n)^p dx = \frac{x^{m+1} (a + bx^n)^{p+1}}{(m+1)a} - \frac{(np + n + m + 1)b}{(m+1)a} \int x^{m+n} (a + bx^n)^p dx.$$

$$(D) \int x^m (a + bx^n)^p dx = -\frac{x^{m+1} (a + bx^n)^{p+1}}{n(p+1)a} + \frac{np + n + m + 1}{n(p+1)a} \int x^m (a + bx^n)^{p+1} dx.$$

While it is not desirable for the student to memorize these formulas, he should know what each one will do and when each one fails. Thus :

Formula (A) diminishes m by n . (A) fails when $np + m + 1 = 0$.

Formula (B) diminishes p by 1. (B) fails when $np + m + 1 = 0$.

Formula (C) increases m by n . (C) fails when $m + 1 = 0$.

Formula (D) increases p by 1. (D) fails when $p + 1 = 0$.

I. To derive formula (A). The formula for integration by parts is

$$(1) \quad \int u \, dv = uv - \int v \, du. \quad (A), \text{ Art. 136}$$

We may apply this formula in the integration of

$$\int x^m (a + bx^n)^p \, dx$$

by placing $u = x^{m-n+1}$ * and $dv = (a + bx^n)^p x^{n-1} \, dx$;

then $du = (m - n + 1)x^{m-n} \, dx$ and $v = \frac{(a + bx^n)^{p+1}}{nb(p+1)}$.

Substituting in (1),

$$(2) \quad \int x^m (a + bx^n)^p \, dx = \frac{x^{m-n+1} (a + bx^n)^{p+1}}{nb(p+1)} - \frac{m-n+1}{nb(p+1)} \int x^{m-n} (a + bx^n)^{p+1} \, dx.$$

$$\begin{aligned} \text{But } \int x^{m-n} (a + bx^n)^{p+1} \, dx &= \int x^{m-n} (a + bx^n)^p (a + bx^n) \, dx \\ &= a \int x^{m-n} (a + bx^n)^p \, dx \\ &\quad + b \int x^m (a + bx^n)^p \, dx. \end{aligned}$$

Substituting this in (2), we get

$$\begin{aligned} \int x^m (a + bx^n)^p \, dx &= \frac{x^{m-n+1} (a + bx^n)^{p+1}}{nb(p+1)} \\ &\quad - \frac{(m-n+1)a}{nb(p+1)} \int x^{m-n} (a + bx^n)^p \, dx \\ &\quad - \frac{m-n+1}{n(p+1)} \int x^m (a + bx^n)^p \, dx. \end{aligned}$$

Transposing the last term to the first member, combining, and solving for $\int x^m (a + bx^n)^p \, dx$, we obtain (A).

* In order to integrate dx by the power formula it is necessary that x outside the parenthesis shall have the exponent $n - 1$. Subtracting $n - 1$ from m leaves $m - n + 1$ for the exponent of x in u .

It is seen by formula (A) that the integration of $x^m(a + bx^n)^p dx$ is made to depend upon the integration of another differential of the same form in which m is replaced by $m - n$. By repeated applications of formula (A), m may be diminished by any multiple of n .

When $np + m + 1 = 0$, formula (A) evidently fails (the denominator vanishing). But in that case

$$\frac{m+1}{n} + p = 0;$$

hence we can apply the method of Art. 169, and the formula is not needed.

II. To derive formula (B). Separating the factors, we may write

$$\begin{aligned} (3) \quad \int x^m(a + bx^n)^p dx &= \int x^m(a + bx^n)^{p-1}(a + bx^n) dx \\ &= a \int x^m(a + bx^n)^{p-1} dx \\ &\quad + b \int x^{m+n}(a + bx^n)^{p-1} dx. \end{aligned}$$

Now let us apply formula (A) to the last term of (3) by substituting in the formula $m + n$ for m , and $p - 1$ for p . This gives

$$\begin{aligned} b \int x^{m+n}(a + bx^n)^{p-1} dx &= \frac{x^{m+1}(a + bx^n)^p}{np + m + 1} \\ &\quad - \frac{a(m+1)}{np + m + 1} \int x^m(a + bx^n)^{p-1} dx. \end{aligned}$$

Substituting this in (3), and combining like terms, we get (B).

Each application of formula (B) diminishes p by unity. Formula (B) fails for the same case as (A).

III. To derive formula (C). Solving formula (A) for

$$\int x^{m-n}(a + bx^n)^p dx,$$

and substituting $m + n$ for m , we get (C).

Therefore each time we apply (C), m is replaced by $m + n$. When $m + 1 = 0$, formula (C) fails, but then the differential expression can be rationalized by the method of Art. 169, and the formula is not needed.

IV. To derive formula (D). Solving formula (B) for

$$\int x^m(a + bx^n)^{p-1} dx,$$

and substituting $p + 1$ for p , we get (D).

Each application of (*D*) increases p by unity. Evidently (*D*) fails when $p + 1 = 0$, but then $p = -1$ and the expression is rational.

Formula (5) of Case IV, Art. 167, is a special case of (*D*), when $m = 0$, $p = -n$, $n = 2$, $a = a^2$, $b = 1$.

ILLUSTRATIVE EXAMPLE 1. $\int \frac{x^3 dx}{\sqrt{1-x^2}} = -\frac{1}{3} (x^2 + 2)(1-x^2)^{\frac{1}{2}} + C.$

Solution. Here $m = 3$, $n = 2$, $p = -\frac{1}{2}$, $a = 1$, $b = -1$.

We apply reduction formula (*A*) in this case because the integration of the differential would then depend on the integration of $\int x(1-x^2)^{-\frac{1}{2}} dx$, which comes under the power formula. Hence, substituting in (*A*), we obtain

$$\begin{aligned} \int x^3(1-x^2)^{-\frac{1}{2}} dx &= \frac{x^{3-2+1}(1-x^2)^{-\frac{1}{2}+1}}{-1(-1+3+1)} - \frac{1(3-2+1)}{-1(-1+3+1)} \int x^{1-2}(1-x^2)^{-\frac{1}{2}} dx \\ &= -\frac{1}{3} x^2(1-x^2)^{\frac{1}{2}} + \frac{2}{3} \int x(1-x^2)^{-\frac{1}{2}} dx \\ &= -\frac{1}{3} x^2(1-x^2)^{\frac{1}{2}} - \frac{2}{3} (1-x^2)^{\frac{1}{2}} + C \\ &= -\frac{1}{3} (x^2+2)(1-x^2)^{\frac{1}{2}} + C. \end{aligned}$$

ILLUSTRATIVE EXAMPLE 2. $\int \frac{x^4 dx}{(a^2-x^2)^{\frac{1}{2}}} = -\left(\frac{1}{4} x^3 + \frac{3}{8} a^2 x\right) \sqrt{a^2-x^2} + \frac{3}{8} a^4 \arcsin \frac{x}{a} + C.$

HINT. Apply (*A*) twice.

ILLUSTRATIVE EXAMPLE 3. $\int (a^2+x^2)^{\frac{1}{2}} dx = \frac{x}{2} \sqrt{a^2+x^2} + \frac{a^2}{2} \ln(x + \sqrt{a^2+x^2}) + C.$

HINT. Here $m = 0$, $n = 2$, $p = \frac{1}{2}$, $a = a^2$, $b = 1$. Apply (*B*) once.

ILLUSTRATIVE EXAMPLE 4. $\int \frac{dx}{x^3 \sqrt{x^2-1}} = \frac{(x^2-1)^{\frac{1}{2}}}{2x^2} + \frac{1}{2} \arcsin \frac{1}{x} + C.$

HINT. Apply (*C*) once.

PROBLEMS

Work out each of the following integrals.

1. $\int \frac{x^2 dx}{\sqrt{a^2-x^2}} = -\frac{x}{2} \sqrt{a^2-x^2} + \frac{a^2}{2} \arcsin \frac{x}{a} + C.$

2. $\int \frac{x^3 dx}{\sqrt{a^2+x^2}} = \frac{1}{3} (x^2-2a^2) \sqrt{a^2+x^2} + C.$

3. $\int \frac{x^5 dx}{\sqrt{1-x^2}} = -\frac{1}{15} (3x^4+4x^2+8) \sqrt{1-x^2} + C.$

4. $\int x^2 \sqrt{a^2-x^2} dx = \frac{x}{8} (2x^2-a^2) \sqrt{a^2-x^2} + \frac{a^4}{8} \arcsin \frac{x}{a} + C.$

5. $\int \frac{dx}{(a^2+x^2)^2} = \frac{x}{2a^2(a^2+x^2)} + \frac{1}{2a^3} \arctan \frac{x}{a} + C.$

$$6. \int \frac{dx}{x^3 \sqrt{a^2 - x^2}} = -\frac{\sqrt{a^2 - x^2}}{2 a^2 x^2} + \frac{1}{2 a^3} \ln \frac{a - \sqrt{a^2 - x^2}}{x} + C.$$

$$7. \int \frac{x^3 dx}{(a^2 + x^2)^{\frac{3}{2}}} = \frac{x^2 + 2 a^2}{\sqrt{a^2 + x^2}} + C.$$

$$8. \int \frac{dx}{(a^2 - x^2)^{\frac{5}{2}}} = \frac{x(3 a^2 - 2 x^2)}{3 a^4 (a^2 - x^2)^{\frac{3}{2}}} + C.$$

$$9. \int (x^2 + a^2)^{\frac{3}{2}} dx = \frac{1}{8} x(2 x^2 + 5 a^2) \sqrt{x^2 + a^2} + \frac{3}{8} a^4 \ln (x + \sqrt{x^2 + a^2}) + C.$$

$$10. \int x^2 \sqrt{x^2 + a^2} dx = \frac{1}{8} x(2 x^2 + a^2) \sqrt{x^2 + a^2} - \frac{1}{8} a^4 \ln (x + \sqrt{x^2 + a^2}) + C.$$

$$11. \int \frac{x^2 dx}{\sqrt{2 ax - x^2}} = -\frac{(x + 3 a) \sqrt{2 ax - x^2}}{2} + \frac{3 a^2}{2} \arccos \left(1 - \frac{x}{a}\right) + C.$$

HINT. $\int \frac{x^2 dx}{\sqrt{2 ax - x^2}} = \int x^{\frac{3}{2}} (2 a - x)^{-\frac{1}{2}} dx$. Apply (A) twice.

$$12. \int \frac{y^3 dy}{\sqrt{4 y - y^2}} = -\frac{1}{3} (y^2 + 5 y + 30) \sqrt{4 y - y^2} + 20 \arccos \left(1 - \frac{y}{2}\right) + C.$$

$$13. \int \frac{ds}{(a^2 + s^2)^3} = \frac{s}{4 a^2 (a^2 + s^2)^2} + \frac{3 s}{8 a^4 (a^2 + s^2)} + \frac{3}{8 a^5} \arctan \frac{s}{a} + C.$$

$$14. \int \frac{y^2 dy}{\sqrt{9 - 4 y^2}} = -\frac{1}{8} y \sqrt{9 - 4 y^2} + \frac{9}{16} \arcsin \frac{2 y}{3} + C.$$

$$15. \int \frac{t^3 dt}{\sqrt{1 + 4 t^2}} = \frac{1}{24} (2 t^2 - 1) \sqrt{1 + 4 t^2} + C.$$

$$16. \int y^2 \sqrt{4 - 9 y^2} dy = \frac{1}{36} y(9 y^2 - 2) \sqrt{4 - 9 y^2} + \frac{2}{27} \arcsin \frac{3 y}{2} + C.$$

$$17. \int \frac{t^3 dt}{(1 + 9 t^2)^{\frac{3}{2}}} = \frac{9 t^2 + 2}{81 \sqrt{1 + 9 t^2}} + C.$$

$$18. \int t^2 \sqrt{1 + 4 t^2} dt = \frac{1}{32} t(1 + 8 t^2) \sqrt{1 + 4 t^2} - \frac{1}{64} \ln (2 t + \sqrt{1 + 4 t^2}) + C.$$

Work out each of the following integrals.

$$19. \int \frac{x^2 dx}{(a^2 - x^2)^2}.$$

$$22. \int \frac{x^8 dx}{\sqrt{4 - x^6}}.$$

$$25. \int \frac{s^7 ds}{(a + bs^4)^{\frac{3}{2}}}.$$

$$20. \int \frac{dx}{x^2(1 + x^2)^{\frac{3}{2}}}.$$

$$23. \int \frac{\sqrt{a^2 + x^2} dx}{x}.$$

$$26. \int \frac{z^8 dz}{\sqrt{5 - z^3}}.$$

$$21. \int \frac{\sqrt{a^2 - x^2} dx}{x^4}.$$

$$24. \int \frac{(1 - x^3)^{\frac{5}{2}} dx}{x}.$$

$$27. \int \frac{dx}{(1 + 4 x^2)^2}.$$

$$28. \int \frac{dt}{t^3 \sqrt{1 - 4 t^2}}.$$

$$29. \int (9 y^2 + 4)^{\frac{3}{2}} dy.$$

175. Reduction formulas for trigonometric differentials. The method of the last article, which makes the given integral depend on another integral of the same form, is called *successive reduction*.

We shall now apply the same method to trigonometric differentials by deriving and illustrating the use of the following trigonometric reduction formulas:

$$(E) \quad \int \sin^m x \cos^n x \, dx = \frac{\sin^{m+1} x \cos^{n-1} x}{m+n} + \frac{n-1}{m+n} \int \sin^m x \cos^{n-2} x \, dx.$$

$$(F) \quad \int \sin^m x \cos^n x \, dx = -\frac{\sin^{m-1} x \cos^{n+1} x}{m+n} + \frac{m-1}{m+n} \int \sin^{m-2} x \cos^n x \, dx.$$

$$(G) \quad \int \sin^m x \cos^n x \, dx = -\frac{\sin^{m+1} x \cos^{n+1} x}{n+1} + \frac{m+n+2}{n+1} \int \sin^m x \cos^{n+2} x \, dx.$$

$$(H) \quad \int \sin^m x \cos^n x \, dx = \frac{\sin^{m+1} x \cos^{n+1} x}{m+1} + \frac{m+n+2}{m+1} \int \sin^{m+2} x \cos^n x \, dx.$$

Here the student should note that

Formula (E) diminishes n by 2. (E) fails when $m+n=0$.

Formula (F) diminishes m by 2. (F) fails when $m+n=0$.

Formula (G) increases n by 2. (G) fails when $n+1=0$.

Formula (H) increases m by 2. (H) fails when $m+1=0$.

To derive these we apply, as before, the formula for integration by parts, namely,

$$(1) \quad \int u \, dv = uv - \int v \, du. \quad (A), \text{ Art. 136}$$

Let $u = \cos^{n-1} x$, and $dv = \sin^m x \cos x \, dx$;

then $du = -(n-1)\cos^{n-2} x \sin x \, dx$, and $v = \frac{\sin^{m+1} x}{m+1}$.

Substituting in (1), we get

$$(2) \quad \int \sin^m x \cos^n x \, dx = + \frac{\sin^{m+1} x \cos^{n-1} x}{m+1} + \frac{n-1}{m+1} \int \sin^{m+2} x \cos^{n-2} x \, dx.$$

In the same way, if we let

$$u = \sin^{m-1} x, \quad \text{and} \quad dv = \cos^n x \sin x \, dx,$$

we obtain

$$(3) \quad \int \sin^m x \cos^n x \, dx = -\frac{\sin^{m-1} x \cos^{n+1} x}{n+1} \\ + \frac{m-1}{n+1} \int \sin^{m-2} x \cos^{n+2} x \, dx.$$

$$\text{But } \int \sin^{m+2} x \cos^{n-2} x \, dx = \int \sin^m x (1 - \cos^2 x) \cos^{n-2} x \, dx \\ = \int \sin^m x \cos^{n-2} x \, dx - \int \sin^m x \cos^n x \, dx.$$

Substituting this in (2), combining like terms, and solving for $\int \sin^m x \cos^n x \, dx$, we get (E).

Making a similar substitution in (3), we get (F).

Solving formula (E) for the integral on the right-hand side, and increasing n by 2, we get (G).

In the same way we get (H) from formula (F).

Formulas (E) and (F) fail when $m+n=0$, formula (G) when $n+1=0$, and formula (H) when $m+1=0$. But in such cases we may integrate by methods which have been explained previously.

It is clear that when m and n are integers, the integral

$$\int \sin^m x \cos^n x \, dx$$

may be made to depend, by using one of the above reduction formulas, upon one of the following integrals:

$$\int dx, \quad \int \sin x \, dx, \quad \int \cos x \, dx, \quad \int \sin x \cos x \, dx, \quad \int \frac{dx}{\sin x} = \int \csc x \, dx, \\ \int \frac{dx}{\cos x} = \int \sec x \, dx, \quad \int \frac{dx}{\cos x \sin x}, \quad \int \tan x \, dx, \quad \int \cot x \, dx,$$

all of which we have learned how to integrate.

ILLUSTRATIVE EXAMPLE 1. Prove

$$\int \sin^2 x \cos^4 x \, dx = -\frac{\sin x \cos^5 x}{6} + \frac{\sin x \cos^3 x}{24} + \frac{1}{16} (\sin x \cos x + x) + C.$$

Solution. First applying formula (F), we get

$$(4) \quad \int \sin^2 x \cos^4 x \, dx = -\frac{\sin x \cos^5 x}{6} + \frac{1}{6} \int \cos^4 x \, dx.$$

[Here $m=2$, $n=4$.]

Applying formula (E) to the integral in the second member of (4), we get

$$(5) \quad \int \cos^4 x \, dx = \frac{\sin x \cos^3 x}{4} + \frac{3}{4} \int \cos^2 x \, dx.$$

[Here $m = 0$, $n = 4$.]

Applying formula (E) to the second member of (5) gives

$$(6) \quad \int \cos^2 x \, dx = \frac{\sin x \cos x}{2} + \frac{x}{2}.$$

Now substitute the result (6) in (5), and then this result in (4). This gives the answer as above.

ILLUSTRATIVE EXAMPLE 2. Prove

$$\int \frac{\tan^2 2x}{\cos 2x} \, dx = \frac{1}{4} \sec 2x \tan 2x - \frac{1}{4} \ln (\sec 2x + \tan 2x) + C.$$

Solution.
$$\frac{\tan^2 2x}{\cos 2x} = \frac{\sin^2 2x}{\cos^2 2x} \cdot \frac{1}{\cos 2x} = \frac{\sin^2 2x}{\cos^3 2x}.$$

Let $2x = u$. Then $x = \frac{1}{2}u$, $dx = \frac{1}{2}du$, and

$$(7) \quad \int \sin^2 2x \cos^{-3} 2x \, dx = \frac{1}{2} \int \sin^2 u \cos^{-3} u \, du.$$

Apply (G) to the new integral in (7), with $m = 2$, $n = -3$, replacing x by u .

$$(8) \quad \int \sin^2 u \cos^{-3} u \, du = -\frac{\sin^3 u \cos^{-2} u}{-2} + \frac{1}{-2} \int \sin^2 u \cos^{-1} u \, du.$$

Apply (F) to the new integral in (8), with $m = 2$, $n = -1$.

$$(9) \quad \int \sin^2 u \cos^{-1} u \, du = -\sin u + \int \cos^{-1} u \, du = -\sin u + \ln (\sec u + \tan u).$$

Substituting from (9) and (8) into (7), reducing, and setting $u = 2x$, we have the answer.

PROBLEMS

Verify the following integrations.

$$1. \int \sin^4 x \cos^2 x \, dx = \sin x \cos x \left[\frac{1}{6} \sin^4 x - \frac{1}{24} \sin^2 x - \frac{1}{16} \right] + \frac{x}{16} + C.$$

$$2. \int \tan^3 \frac{x}{3} \, dx = \frac{3}{2} \tan^2 \frac{x}{3} + 3 \ln \cos \frac{x}{3} + C.$$

$$3. \int \csc^4 \theta \, d\theta = -\frac{\csc^3 \theta}{3} + \csc \theta + \theta + C.$$

$$4. \int \sec^3 t \, dt = \frac{1}{2} \sec t \tan t + \frac{1}{2} \ln (\sec t + \tan t) + C.$$

$$5. \int \csc^3 x \, dx = -\frac{1}{2} \csc x \csc x + \frac{1}{2} \ln (\csc x - \csc x) + C.$$

$$6. \int \csc^5 \theta \, d\theta = -\frac{\csc \theta \csc \theta}{4} \left(\csc^2 \theta + \frac{3}{2} \right) + \frac{3}{8} \ln (\csc \theta - \csc \theta) + C.$$

$$7. \int \sin^2 \phi \cos^2 \phi \, d\phi = \frac{1}{8} \sin \phi \cos \phi (2 \sin^2 \phi - 1) + \frac{1}{8} \phi + C.$$

8. $\int \frac{\csc^2 2\theta \, d\theta}{\sin 2\theta} = -\frac{1}{4} \csc 2\theta \sec 2\theta - \frac{1}{4} \ln (\sec 2\theta - \csc 2\theta) + C.$
9. $\int \frac{dx}{\sin^4 x} = -\frac{\cos x}{3 \sin^3 x} - \frac{2 \cos x}{3 \sin x} + C.$
10. $\int \cos^6 \theta \, d\theta = \frac{\cos \theta \sin \theta}{48} [8 \cos^4 \theta + 10 \cos^2 \theta + 15] + \frac{5 \theta}{16} + C.$
11. $\int_0^{\frac{\pi}{2}} \sin^4 \theta \, d\theta = \frac{3 \pi}{16}.$
12. $\int_0^{\pi} \cos^4 x \, dx = \frac{3 \pi}{8}.$
14. $\int_0^{\pi} \sin^8 \phi \, d\phi = \frac{35 \pi}{128}.$
13. $\int_0^{\frac{\pi}{2}} \sin^6 2\theta \, d\theta = \frac{5 \pi}{32}.$
15. $\int_{\frac{\pi}{4}}^{\frac{\pi}{2}} \frac{\cos^4 x \, dx}{\sin^2 x} = \frac{5}{4} - \frac{3 \pi}{8}.$

Work out each of the following integrals:

16. $\int \sin^6 2\theta \, d\theta.$
18. $\int \frac{\sin^3 x \, dx}{\cos^5 x}.$
20. $\int_0^{\frac{\pi}{2}} \tan^3 \frac{\theta}{2} \, d\theta.$
17. $\int \csc^3 \frac{\theta}{2} \, d\theta.$
19. $\int \frac{d\theta}{\sin^4 \theta \cos^2 \theta}.$
21. $\int_0^{\pi} \sin^4 x \, dx.$
22. $\int_0^{\frac{\pi}{2}} \sin^3 \theta \cos^3 \theta \, d\theta.$
23. $\int_0^{\frac{\pi}{2}} (1 + \sin \theta)^4 \, d\theta.$

176. Use of a table of integrals. The methods of integration developed in Chapters XII, XVI, and XVII have been directed to reducing a given integral to one or more of the Standard Elementary Forms in Art. 128. Various devices have been elaborated to this end, such as

integration by parts (Art. 136);
integration by partial fractions (Art. 167);
integration by substitution of a new variable (Arts. 168–172);
use of reduction formulas (Arts. 174–175).

When, however, a more or less extensive table of integrals is available, the first step in any problem in formal integration is to search for a formula in the table by which the problem can be solved without the use of any of these devices. Such a table is given in Chapter XXVII. Some examples will now be given.

ILLUSTRATIVE EXAMPLE 1. Prove, by the Table of Integrals,

$$\int \frac{dx}{x^2(2+x)} = -\frac{1}{2x} + \frac{1}{4} \ln \left(\frac{2+x}{x} \right) + C.$$

Solution. Use 14, with $a = 2$, $b = 1$, and $u = x$.

This example, without the table, would be worked out as in Case II, Art. 167.

ILLUSTRATIVE EXAMPLE 2. Verify, by the Table of Integrals,

$$\int \frac{dx}{x(9 + 4x^2)} = \frac{1}{18} \ln \left(\frac{x^2}{9 + 4x^2} \right) + C.$$

Solution. Use 22, with $a = 3$, $b = 2$, and $u = x$.

This example, without the table, is solved as in Case III, Art. 167.

ILLUSTRATIVE EXAMPLE 3. Verify, by the Table of Integrals,

$$\int \frac{dx}{x\sqrt{4+3x}} = \frac{1}{2} \ln \frac{\sqrt{4+3x}-2}{\sqrt{4+3x}+2} + C.$$

Solution. Use 31, with $a = 4$, $b = 3$, and $u = x$.

This example, without the table, is worked out by the substitution $4 + 3x = z^2$, as shown in Art. 168.

ILLUSTRATIVE EXAMPLE 4. Verify, by the Table of Integrals,

$$\int \frac{x dx}{\sqrt{3x^2+4x-7}} = \frac{\sqrt{3x^2+4x-7}}{3} - \frac{2}{3\sqrt{3}} \ln (6x+4+2\sqrt{3}\sqrt{3x^2+4x-7}) + C.$$

Solution. Use 113, with $a = -7$, $b = 4$, $c = 3$, and $u = x$.

Without the table the example would be solved by completing the square as in Illustrative Example 2, p. 206.

ILLUSTRATIVE EXAMPLE 5. Verify, by the Table of Integrals,

$$\int e^{3x} \cos 2x dx = \frac{e^{3x}(2 \sin 2x + 3 \cos 2x)}{13} + C.$$

Solution. Use 154, with $a = 3$, $n = 2$, $u = x$.

Without the table the example would be solved by integration by parts. See Illustrative Example 6, Art. 136.

In many problems the given integral cannot be identified with one in the table as easily as in the preceding examples. In such cases we search for a formula in the table similar to the given integral, and such that the latter can be transformed into the former by a simple change of variable. This method has been used constantly in Chapter XII and in all integration problems hitherto.

ILLUSTRATIVE EXAMPLE 6. Verify, by the Table of Integrals,

$$\int \frac{dx}{x\sqrt{4x^2+9}} = \frac{1}{3} \ln \frac{2x}{3+\sqrt{4x^2+9}} + C.$$

Solution. Formula 47 is similar. Let $u = 2x$. Then $x = \frac{1}{2}u$, $dx = \frac{1}{2}du$, and, substituting the values in the given integral, we obtain

$$\int \frac{dx}{x\sqrt{4x^2+9}} = \int \frac{\frac{1}{2}du}{\frac{1}{2}u\sqrt{u^2+9}} = \int \frac{du}{u\sqrt{u^2+9}}.$$

Hence, applying 47, with $a = 3$, and substituting back $u = 2x$, $a = 3$, we have

$$\int \frac{dx}{x\sqrt{4x^2+9}} = -\frac{1}{3} \ln \left(\frac{3+\sqrt{4x^2+9}}{2x} \right) + C.$$

Without tables we should proceed as in Illustrative Example 2, Art. 135.

ILLUSTRATIVE EXAMPLE 7. Verify, by the Table of Integrals,

$$\int \frac{\sqrt{9x-4x^2}}{x^3} dx = -\frac{2}{27} \frac{(9x-4x^2)^{\frac{3}{2}}}{x^3} + C.$$

Solution. Formula 84 is similar. Let $u = 2x$. Then $x = \frac{1}{2}u$, $dx = \frac{1}{2}du$. Substituting, we obtain

$$\int \frac{\sqrt{9x-4x^2}}{x^3} dx = \int \frac{\sqrt{\frac{9}{8}u-u^2}}{\frac{1}{8}u^3} \frac{du}{2} = 4 \int \frac{\sqrt{\frac{9}{8}u-u^2}}{u^3} du.$$

This is now 84 with $a = \frac{9}{8}$. Hence, applying 84, and substituting back $u = 2x$, we get the required result.

If no formula from the table can be applied as in the preceding two cases, there remains the possibility that the use of one or more of the devices mentioned at the beginning of this article will lead to new integrals solvable by the table. No general directions can be given other than the rules already developed in the text for the employment of these devices.

The student should study the arrangement of the table. He will find that the Standard Forms of Art. 128 appear in their proper places. The reduction formulas of Art. 174 are given, with modifications, by 96-104. Also, the reduction formulas of Art. 175, with additional ones for various cases, are numbered 157-174. Increased power in the technique of integration will come from familiarity with the table and practice in using it.

PROBLEMS

Work out the following integrals.

- $\int x^3 \sqrt{x^2 + 5} dx = \frac{1}{15} (3x^2 - 10)(x^2 + 5)^{\frac{3}{2}} + C.$
- $\int \frac{dt}{(1-4t^2)^{\frac{3}{2}}} = \frac{t}{\sqrt{1-4t^2}} + C.$
- $\int \frac{x^2 dx}{\sqrt{9x^2-4}} = \frac{x}{18} \sqrt{9x^2-4} + \frac{2}{27} \ln(3x + \sqrt{9x^2-4}) + C.$
- $\int \frac{d\theta}{2 - \cos 2\theta} = \frac{1}{\sqrt{3}} \arctan(\sqrt{3} \tan \theta) + C.$
- $\int \frac{x^5 dx}{(1-x^4)^{\frac{3}{2}}} = \frac{x^2}{2\sqrt{1-x^4}} - \frac{1}{2} \arcsin x^2 + C.$
- $\int \frac{(a^2-x^2)^{\frac{3}{2}} dx}{x^2} = -\frac{(x^2+2a^2)\sqrt{a^2-x^2}}{2x} - \frac{3a^2}{2} \arcsin \frac{x}{a} + C.$
- $\int e^t \sin^2 \frac{t}{2} dt = \frac{1}{4} e^t (2 - \sin t - \cos t) + C.$

8. $\int \frac{\sin 2\theta d\theta}{1 + \cos \theta} = 2 \ln (1 + \cos \theta) - 2 \cos \theta + C.$
9. $\int \frac{dx}{2 + 2x + x^2} = \arctan (x + 1) + C.$
10. $\int x^3 \sin x^2 dx = \frac{1}{2} \sin x^2 - \frac{1}{2} x^2 \cos x^2 + C.$
11. $\int \frac{dx}{\sqrt{(x-1)(2-x)}} = 2 \arcsin \sqrt{x-1} + C.$
12. $\int \frac{\sqrt{9t^2+4} dt}{t} = \sqrt{9t^2+4} - 2 \ln \left(\frac{2 + \sqrt{9t^2+4}}{t} \right) + C.$
13. $\int \frac{du}{u^4 \sqrt{a^2 - u^2}} = -\frac{(a^2 + 2u^2)\sqrt{a^2 - u^2}}{3a^4 u^3} + C.$
14. $\int \frac{dx}{x^2 \sqrt{4-x}} = \frac{1}{16} \ln \left(\frac{\sqrt{4-x}-2}{\sqrt{4-x}+2} \right) - \frac{\sqrt{4-x}}{4x} + C.$

Work out each of the following integrals.

15. $\int \frac{x^5 dx}{5 + 4x^2}.$
20. $\int \frac{\sqrt{4x^2 - 25} dx}{x^2}.$
25. $\int \frac{d\theta}{3 + 5 \sin 2\theta}.$
16. $\int (a^2 - u^2)^{\frac{3}{2}} du.$
21. $\int \frac{x^3 dx}{\sqrt{a + bx^2}}.$
26. $\int \frac{dx}{x^4 \sqrt{x^6 + a^6}}.$
17. $\int \frac{dx}{x^2 + 4x + 2}.$
22. $\int \frac{dy}{y^2 \sqrt{y-1}}.$
27. $\int \frac{x dx}{\sqrt{x^2 + 2x + 4}}.$
18. $\int \frac{\csc t dt}{a + b \sin t}.$
23. $\int \sqrt{\frac{3+x^2}{2+x^2}} x dx.$
28. $\int \frac{x dx}{\sqrt{4 + 2x - x^2}}.$
19. $\int \sqrt{\frac{1+2y}{1-2y}} dy.$
24. $\int \frac{d\theta}{5 + 3 \sin 2\theta}.$
29. $\int \frac{dx}{(1 + e^x)^2}.$
30. $\int \frac{\sqrt{x^3 - 1} dx}{x}.$
32. $\int e^t \cos^2 t dt.$
31. $\int \frac{\sqrt{x+4} dx}{x}.$
33. $\int \frac{\csc \theta d\theta}{4 + \sin^2 \theta}.$

Evaluate each of the following definite integrals.

34. $\int_0^3 \frac{x dx}{(1+x)^2} = 0.636.$
37. $\int_1^2 \frac{dt}{t(5-t^2)} = 0.277.$
35. $\int_1^{\frac{5}{3}} \frac{dx}{x^2 \sqrt{25-9x^2}} = \frac{4}{25}.$
38. $\int_0^2 (4x^2 + 9)^{\frac{3}{2}} dx = 112.9.$
36. $\int_0^2 \frac{dx}{(4x^2 + 9)^{\frac{3}{2}}} = \frac{2}{45}.$
39. $\int_{-a}^a \sqrt{\frac{a-u}{a+u}} du = \pi a.$

$$40. \int_1^2 \frac{x^2 dx}{\sqrt{9-2x^2}} = 1.338.$$

$$42. \int_1^2 \frac{\sqrt{9-2x^2} dx}{x} = 1.467.$$

$$41. \int_1^2 \frac{\sqrt{9-2x^2} dx}{x^2} = 1.129.$$

$$43. \int_0^1 t^2 e^{-t} dt = 0.1605.$$

$$44. \int_1^2 \frac{dy}{y^3 \sqrt{4y^2+5}}.$$

$$46. \int_0^2 \frac{x^2 dx}{(4x^2+9)^{3/2}}.$$

$$48. \int_1^3 \frac{dx}{x\sqrt{4x^2+1}}.$$

$$45. \int_0^{\pi/2} \cos^2 \theta \sin^4 \theta d\theta.$$

$$47. \int_0^1 e^{-t/5} \cos \frac{1}{2} \pi t dt.$$

$$49. \int_0^{\pi} \phi \cos \frac{1}{3} \phi d\phi.$$

ADDITIONAL PROBLEMS

1. Verify the following results.

$$(a) \int_1^{e^2} \frac{dx}{x(1+\ln x)} = \ln 3;$$

$$(b) \int_1^{e^2} \frac{dx}{x(1+\ln x)^2} = \frac{2}{3}.$$

2. A parabola with its axis parallel to the y -axis passes through the origin and the point $(1, 2)$. Find its equation if the area between the parabola and the x -axis is a maximum or a minimum.

Ans. $y = 6x - 4x^2$ gives a minimum.

3. Sketch the curve $y\sqrt{x} = \ln x$. Find the volume of the solid of revolution formed by revolving about the x -axis the area bounded by the curve, the x -axis, and two ordinates, one through the maximum point and the other through the point of inflection.

Ans. $\frac{2}{81} \pi$.

4. A solid right circular cone of metal is formed so that the density at any point P is $20(5-r)$ lb. per cubic foot, where r is the distance in feet of the point P from the axis of the cone. Find the weight of the cone if its altitude and the radius of the base are each 3 ft.

Ans. 630π lb.

NOTE. The weight of an element of uniform density is its volume times its density.

5. A hollow metal sphere has an inside radius of 6 in. and an outside radius of 10 in. The density of the metal at any point varies inversely as the distance of the point from the center of the sphere, and at the outside surface the density is 2 oz. per cubic inch. Find the weight of the sphere.

Ans. 2560π oz.

6. If n is an even integer, show that

$$\int_0^{\frac{\pi}{2}} \sin^n x dx = \int_0^{\frac{\pi}{2}} \cos^n x dx = \frac{(n-1)(n-3) \cdots (1)}{n(n-2) \cdots (2)} \frac{\pi}{2}.$$

7. If n is an odd integer, find the value of

$$\int_0^{\frac{\pi}{2}} \sin^n x dx.$$

CHAPTER XVIII

CENTROIDS, FLUID PRESSURE, AND OTHER APPLICATIONS

177. Moment of area; centroids. The *centroid* of a plane area is defined in the following manner.

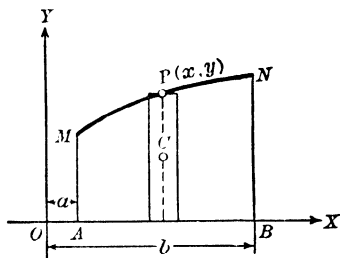
A piece of stiff, flat cardboard will balance in a horizontal position if supported at a point directly under its center of gravity. This point of support is the *centroid* of the area of the flat surface of the cardboard.

For certain areas considered in elementary geometry the centroids are obvious. For a rectangle or a circle the centroid coincides with the geometrical center. In fact, if a plane figure possesses a center of symmetry, that point is the centroid. Furthermore, if a plane figure has an axis of symmetry, the centroid will lie on that axis.

The following considerations lead to the determination of the centroid by mathematical means. It is beyond the purpose of this book to justify the argument by mechanics.

Consider the area $AMPNB$ of the figure. Divide it into n rectangles, each with base Δx , as heretofore. The figure shows one of these rectangles. Let dA be its area, and $C(h, k)$ its centroid. Then

$$(1) \quad dA = y \, dx, \quad h = x, \quad k = \frac{1}{2} y.$$



The *moment of area* of this elementary rectangle about OX (or OY) is the product of its area by the perpendicular distance of its centroid from OX (or OY). If these moments are, respectively, dM_x and dM_y , then

$$(A) \quad dM_x = k \, dA, \quad dM_y = h \, dA.$$

The *moment of area* for the figure $AMPNB$ is obtained by applying the Fundamental Theorem (Art. 156) to the sum of the moments of area of the n elementary rectangles. Thus we obtain

$$(B) \quad M_x = \int k \, dA, \quad M_y = \int h \, dA.$$

Finally, if (\bar{x}, \bar{y}) is the centroid of the area $AMPNB$, and A its area, then the relations between the moments of area (B) and \bar{x} and \bar{y} are given by

$$(C) \quad A\bar{x} = M_y, \quad A\bar{y} = M_x.$$

To calculate (\bar{x}, \bar{y}) , find the moments of area M_x and M_y . From (1) and (B), these are, for the above figure,

$$(2) \quad M_x = \frac{1}{2} \int_a^b y^2 dx, \quad M_y = \int_a^b xy dx,$$

in which the value of y in terms of x must be substituted from the equation of the curve MPN .

If the area A is known, we have, from (C),

$$(3) \quad \bar{x} = \frac{M_y}{A}, \quad \bar{y} = \frac{M_x}{A}.$$

If A is not known, it may be found by integration, as in Art. 145.

ILLUSTRATIVE EXAMPLE 1. Find the centroid of the area under one arch of the sine curve

$$(4) \quad y = \sin x.$$

Solution. Constructing an elementary rectangle, we have

$$(5) \quad dA = y dx = \sin x dx, \\ dM_x = k dA = \frac{1}{2} y^2 dx = \frac{1}{2} \sin^2 x dx, \quad dM_y = h dA = xy dx = x \sin x dx.$$

The limits are $x = 0, x = \pi$. Hence

$$(6) \quad A = \int_0^\pi \sin x dx = 2, \quad M_x = \frac{1}{2} \int_0^\pi \sin^2 x dx = \frac{1}{4} \pi, \quad M_y = \int_0^\pi x \sin x dx = \pi.$$

Then, from (3), $\bar{x} = \frac{1}{2} \pi, \bar{y} = \frac{1}{8} \pi$. Ans.

The value of \bar{x} might have been anticipated, since the line $x = \frac{1}{2} \pi$ is an axis of symmetry.

ILLUSTRATIVE EXAMPLE 2. In the figure the curve OPA is an arc of the parabola $y^2 = 2px$. Find the centroid of the area $OPAB$.

Solution. Draw an elementary rectangle, as in the figure, and mark its centroid (h, k) . Then

$$dA = x dy, \quad h = \frac{1}{2} x, \quad k = y.$$

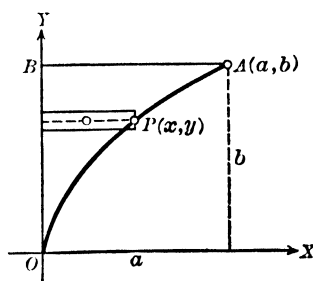
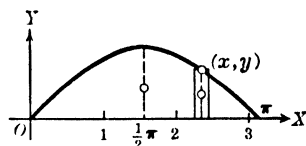
$$\text{Using (A), } dM_x = k dA = xy dy, \\ dM_y = h dA = \frac{1}{2} x^2 dy.$$

Finding x in terms of y from $y^2 = 2px$, and integrating between the limits $y = 0, y = b$, we find

$$A = \frac{b^3}{6p}, \quad M_x = \frac{b^4}{8p}, \quad M_y = \frac{b^5}{40p^2}.$$

Hence $\bar{x} = \frac{3b^2}{20p}, \bar{y} = \frac{3}{4}b$. But $x = a, y = b$ satisfy the equation $y^2 = 2px$.

Hence $b^2 = 2pa$, and $\bar{x} = \frac{3}{10}a$. The centroid is therefore $(\frac{3}{10}a, \frac{3}{4}b)$. Ans.



PROBLEMS

Find the centroid of each of the areas bounded by the following curves.

1. $y^2 = 2px$, $x = h$. *Ans.* $(\frac{2}{3}h, 0)$.

2. $y = x^3$, $x = 2$, $y = 0$. $(\frac{8}{5}, \frac{16}{7})$.

3. $y = x^3$, $y = 4x$. (First quadrant.) $(\frac{1}{15}, \frac{64}{15})$.

4. $x = 4y - y^2$, $y = x$. $(\frac{1}{5}, \frac{3}{5})$.

5. $y^2 = 4x$, $2x - y = 4$. $(\frac{8}{5}, 1)$.

6. $y = x^2$, $y = 2x + 3$. $(1, \frac{17}{5})$.

7. $y = x^2 - 2x - 3$, $y = 6x - x^2 - 3$. $(2, 1)$.

8. $y = x^3$, $y = 8$, $x = 0$.

9. $y = 6x - x^2$, $y = x$.

10. $y = 4x - x^2$, $y = 2x - 3$.

11. $y = x^3 - 3x$, $y = x$. (First quadrant.)

12. $y^2 = a^2 - ax$, $x = 0$, $y = 0$. (First quadrant.)

13. $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$, $y = 0$, $x = 2a$. (First quadrant.)

14. Find the centroid of the area bounded by the coordinate axes and the parabola $\sqrt{x} + \sqrt{y} = \sqrt{a}$. *Ans.* $\bar{x} = \bar{y} = \frac{1}{5}a$.

15. Find the centroid of the area bounded by the loop of the curve $y^2 = 4x^2 - x^3$. *Ans.* $\bar{x} = \frac{16}{7}$, $\bar{y} = 0$.

16. Find the centroid of the portion in the first quadrant of the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$. *Ans.* $\bar{x} = \frac{4a}{3\pi}$, $\bar{y} = \frac{4b}{3\pi}$.

17. Find the centroid of the area bounded by the parabola $y^2 = 2px$ and the line $y = mx$. *Ans.* $\bar{x} = \frac{4p}{5m^2}$, $\bar{y} = \frac{p}{m}$.

18. Find the centroid of the area included by the parabolas $y^2 = ax$ and $x^2 = by$. *Ans.* $\bar{x} = \frac{9}{20}a^{\frac{1}{3}}b^{\frac{2}{3}}$, $\bar{y} = \frac{9}{20}a^{\frac{2}{3}}b^{\frac{1}{3}}$.

19. Find the centroid of the area bounded by the cissoid $y^2(2a - x) = x^3$ and its asymptote $x = 2a$. *Ans.* $\bar{x} = \frac{5}{3}a$, $\bar{y} = 0$.

20. Find the centroid of the area bounded by the witch $x^2y = 4a^2(2a - y)$ and the x -axis. *Ans.* $\bar{x} = 0$, $\bar{y} = \frac{1}{2}a$.

21. Find the distance from the center of the circle to the centroid of the area of a circular sector of angle 2θ . *Ans.* $\frac{2r \sin \theta}{3\theta}$.

22. Find the distance from the center of the circle to the centroid of the area of a circular segment the chord of which subtends a central angle 2θ . *Ans.* $\frac{2r \sin^3 \theta}{3(\theta - \sin \theta \cos \theta)}$.

23. Find the centroid of the area bounded by the cardioid

$$\rho = a(1 + \cos \theta). \quad \text{Ans. } \bar{x} = \frac{5}{8} a, \bar{y} = 0.$$

24. Find the centroid of the area bounded by one loop of the curve

$$\rho = a \cos 2 \theta. \quad \text{Ans. Distance from origin} = \frac{128 a \sqrt{2}}{105 \pi}.$$

25. Find the centroid of the area bounded by one loop of the curve

$$\rho = a \cos 3 \theta. \quad \text{Ans. Distance from origin} = \frac{81 a \sqrt{3}}{80 \pi}.$$

178. Centroid of a solid of revolution. The center of gravity of a homogeneous solid is identical with the centroid of that body considered as a geometrical solid. The centroid will lie in any plane of symmetry which the solid may possess.

To achieve a mathematical definition of the centroid of a solid of revolution, it is necessary to modify the discussion of the preceding article only in the details.

Let OX be the geometrical axis of the solid. The centroid will then lie on this axis. Let dV be an element of volume, that is, a cylinder of revolution with altitude Δx and radius y . Then $dV = \pi y^2 \Delta x$.

The *moment of volume* of this cylinder with respect to the plane through OY perpendicular to OX is

$$(1) \quad dM_y = x dV = \pi x y^2 \Delta x.$$

The *moment of volume for the solid* is then found by the Fundamental Theorem, and \bar{x} is given from

$$(2) \quad V\bar{x} = M_y = \int \pi x y^2 dx.$$

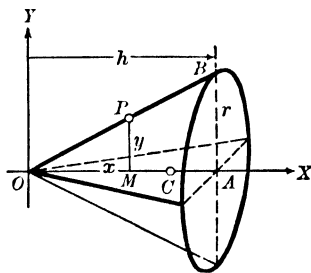
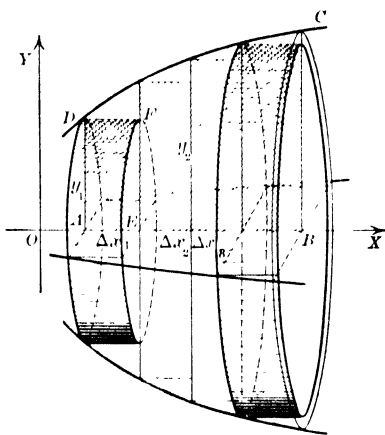
ILLUSTRATIVE EXAMPLE. Find the centroid of a solid cone of revolution.

Solution. The equation of the element OB is

$$\frac{y}{x} = \frac{AB}{OA} = \frac{r}{h}, \quad \text{or} \quad y = \frac{rx}{h}.$$

$$\text{Hence} \quad M_y = \int_0^h \pi x \frac{r^2 x^2}{h^2} dx = \frac{1}{4} \pi r^2 h^2.$$

$$\text{Since } V = \frac{1}{3} \pi r^2 h, \quad \bar{x} = \frac{3}{4} h. \quad \text{Ans.}$$



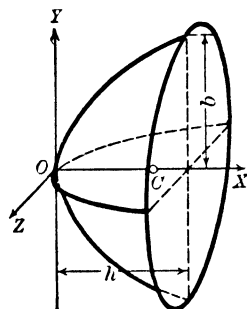
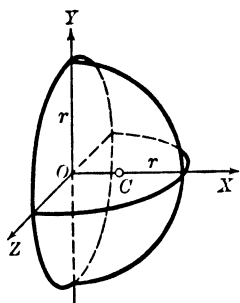
PROBLEMS

Find the centroid for each of the following solids.

1. Hemisphere. (See figure.) *Ans.* $\bar{x} = \frac{3}{8} r$.

2. Paraboloid of revolution. (See figure.)
Ans. $\bar{x} = \frac{3}{8} h$.

The area bounded by OX and each curve given below is revolved about OX . Find the centroid of the solid of revolution generated.



3. $x^2 - y^2 = a^2$, $x = 2a$.

4. $2xy = a^2$, $x = \frac{1}{2}a$, $x = 2a$.

5. $ay = x^2$, $x = a$.

Ans. $\bar{x} = \frac{5}{6}a$.

6. $y^2 = 4x$, $x = 1$, $x = 4$.

7. $x^2 + y^2 = 4$, $x = 0$, $x = 1$.

$\bar{x} = \frac{21}{44}$.

8. $y = a \sin x$, $x = \frac{1}{2}\pi$.

The area bounded by OY and each of the curves given below is revolved about OY . Find the centroid of the solid of revolution generated.

9. $y^2 = 4ax$, $y = b$.

Ans. $\bar{y} = \frac{5}{6}b$.

10. $x^2 - y^2 = 1$, $y = 0$, $y = 1$.

$\bar{y} = \frac{9}{16}$.

11. $ay^2 = x^3$, $y = a$.

12. The radii of the upper and lower bases of a frustum of a cone of revolution are, respectively, 3 in. and 6 in., and the altitude is 8 in. Locate the centroid.

13. Find the centroid of the solid formed by revolving about the y -axis the area in the first quadrant bounded by the lines $y = 0$, $x = a$, and the parabola $y^2 = 4ax$.

Ans. $\bar{y} = \frac{5}{6}a$.

14. Find the centroid of the solid formed by revolving about the x -axis that part of the area of the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ which lies in the first quadrant.

Ans. $\bar{x} = \frac{3}{8}a$.

15. Find the centroid of the solid formed by revolving about the x -axis the area in the first quadrant bounded by the lines $y = 0$, $x = 2a$, and the hyperbola $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$.

16. Find the centroid of the solid formed by revolving about the x -axis the area bounded by the lines $x = 0$, $x = a$, $y = 0$, and the hyperbola $\frac{x^2}{a^2} - \frac{y^2}{b^2} + 1 = 0$.

17. Find the centroid of the solid formed by revolving about the x -axis the area bounded by the lines $y = 0$, $x = \frac{\pi}{4}$, and the curve $y = \sin 2x$.

18. Find the centroid of the solid formed by revolving about the x -axis the area bounded by the lines $x = 0$, $x = a$, $y = 0$, and the curve $y = e^x$.

19. The area bounded by a parabola, its axis, and its latus rectum is revolved about the latus rectum. Find the centroid of the solid generated.

Ans. Distance from focus $= \frac{5}{32}$ of latus rectum.

179. Fluid pressure. We will now take up the study of *fluid pressure* and learn how to calculate the pressure of a fluid on a vertical wall.

Let $ABDC$ represent part of the area of the vertical surface of one wall of a reservoir. It is desired to determine the total fluid pressure on this area. Draw the axes as in the figure, the y -axis lying in the surface of the fluid. Divide AB into n subintervals and construct horizontal rectangles within the area. Then the area of one rectangle (as EP) is $y \Delta x$. If this rectangle was horizontal at the depth x , the fluid pressure on it would be

$$Wxy \Delta x,$$

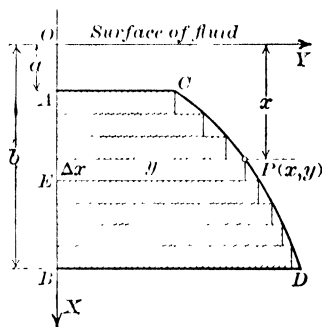
[The pressure of a fluid on any given horizontal surface equals the weight of a column of the fluid standing on that surface as a base and of height equal to the distance of this surface below the surface of the fluid.]

where W = the weight of a unit volume of the fluid. Since fluid pressure is the same in all directions, it follows that $Wxy \Delta x$ will be approximately the pressure on the rectangle EP in its vertical position. Hence the sum

$$\sum_{i=1}^n Wx_i y_i \Delta x_i$$

represents approximately the pressure on all the rectangles. The pressure on the area $ABDC$ is evidently the limit of this sum. Hence, by the Fundamental Theorem,

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n Wx_i y_i \Delta x_i = \int Wxy \, dx.$$



Hence the fluid pressure on a vertical submerged surface bounded by a curve, the x -axis, and the two horizontal lines $x = a$ and $x = b$ is given by the formula

$$(D) \quad \text{Fluid pressure} = W \int_a^b yx \, dx,$$

where the value of y in terms of x must be substituted from the equation of the given curve.

We shall assume 62 lb. ($= W$) as the weight of a cubic foot of water.

ILLUSTRATIVE EXAMPLE 1. A circular water main 6 ft. in diameter is half full of water. Find the pressure on the gate that closes the main.

Solution. The equation of the circle is $x^2 + y^2 = 9$.

$$\text{Hence} \quad y = \sqrt{9 - x^2}, \\ W = 62,$$

and the limits are from $x = 0$ to $x = 3$. Substituting in (D), we get the pressure on the right of the x -axis to be

$$\text{Pressure} = 62 \int_0^3 \sqrt{9 - x^2} \cdot x \, dx = \left[-\frac{62}{2} (9 - x^2)^{\frac{3}{2}} \right]_0^3 = 558.$$

$$\text{Hence} \quad \text{Total pressure} = 2 \times 558 = 1116 \text{ lb. } \text{Ans.}$$

The essential part of the above reasoning is that the pressure ($= dP$) on an elementary horizontal strip is equal (approximately) to the product of the area of the strip ($= dA$) by its depth ($= h$) and the weight ($= W$) of unit volume of the fluid. That is,

$$(E) \quad dP = Wh \, dA.$$

With this in mind, the axes of coördinates may be chosen in any convenient position.

ILLUSTRATIVE EXAMPLE 2. A trapezoidal gate in a dam is shown in the figure. Find the pressure on the gate when the surface of the water is 4 ft. above the top of the gate.

Solution. Choosing axes OX and OY as shown, and drawing an elementary horizontal strip, we have, using (E),

$$dA = 2x \, dy,$$

$$h = 8 - y,$$

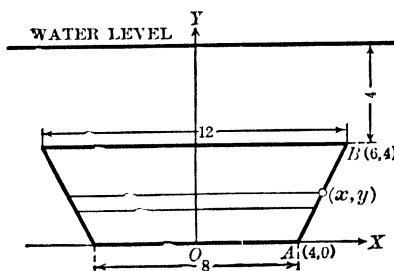
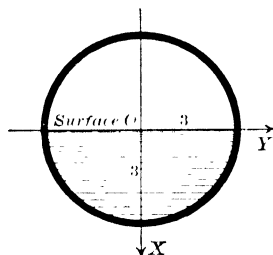
$$dP = W(8 - y)2x \, dy.$$

The equation of AB is $y = 2x - 8$. Solving this equation for x , and substituting, the result is

$$dP = W(8 - y)(y + 8)dy = W(64 - y^2)dy.$$

Integrating with limits $y = 0$ and $y = 4$, we obtain

$$P = W \int_0^4 (64 - y^2)dy = \frac{704}{3} W = 14,549 \text{ lb. } \text{Ans.}$$



PROBLEMS

In the following problems the y -axis is directed vertically upward, and the x -axis is at the surface level of a liquid. Denoting the weight of a cubic unit of the liquid by W , calculate the pressure on the areas formed by joining with straight lines each set of points in the order given.

1. $(0, 0)$, $(3, 0)$, $(0, -6)$, $(0, 0)$. *Ans.* 18 W .

2. $(0, 0)$, $(3, -6)$, $(0, -6)$, $(0, 0)$. 36 W .

3. $(0, 0)$, $(2, -2)$, $(0, -4)$, $(-2, -2)$, $(0, 0)$. 16 W .

4. Calculate the pressure on the lower half of an ellipse whose semi-axes are 2 and 3 units respectively, (a) when the major axis lies in the surface of the liquid; (b) when the minor axis lies in the surface.

Ans. (a) 8 W ; (b) 12 W .

5. Each end of a horizontal oil tank is an ellipse of which the horizontal axis is 12 ft. long and the vertical axis 6 ft. long. Calculate the pressure on one end when the tank is half full of oil weighing 60 lb. per cubic foot.

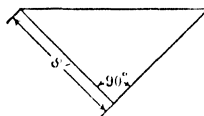
Ans. 2160 lb.

6. The vertical end of a vat is a segment of a parabola (with vertex at the bottom) 8 ft. across the top and 16 ft. deep. Calculate the pressure on this end when the vat is full of a liquid weighing 70 lb. per cubic foot.

Ans. 38,229 lb.

7. The vertical end of a water trough is an isosceles right triangle of which each leg is 8 ft. Calculate the pressure on the end when the trough is full of water ($W = 62.5$).

Ans. 3771 lb.



8. The vertical end of a water trough is an isosceles triangle 5 ft. across the top and 5 ft. deep. Calculate the pressure on the end when the trough is full of water.

Ans. 1302 lb.

9. A horizontal cylindrical tank of diameter 8 ft. is half full of oil weighing 60 lb. per cubic foot. Calculate the pressure on one end.

Ans. 2560 lb.

10. Calculate the pressure on one end if the tank of Problem 9 is full.

11. A rectangular gate in a vertical dam is 10 ft. wide and 6 ft. deep. Find (a) the pressure when the level of the water ($W = 62.5$) is 8 ft. above the top of the gate; (b) how much higher the water must rise to double the pressure found in (a).

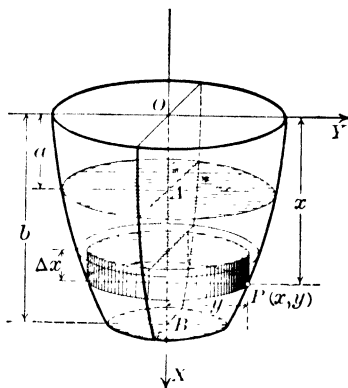
Ans. (a) 41,250 lb.; (b) 11 ft.

12. Show that the pressure on any vertical surface is the product of the weight of a cubic unit of the liquid, the area of the surface, and the depth of the centroid of the area.

13. A vertical cylindrical tank, of diameter 30 ft. and height 50 ft., is full of water. Find the pressure on the curved surface. *Ans.* 3682 tons.

180. Work. In mechanics the work done by a constant force F causing a displacement d is the product Fd . When F is variable, this definition leads to an integral. Two examples will be considered here.

Work done in pumping out a tank. Let us now consider the problem of finding the work done in emptying reservoirs of the form of solids of revolution with their axes vertical. It is convenient to assume the x -axis of the revolved curve as vertical, and the y -axis as on a level with the top of the reservoir.



Consider a reservoir such as the one shown; we wish to calculate the work done in emptying it of a fluid from the depth a to the depth b .

Divide AB into n subintervals, pass planes perpendicular to the axis of revolution through these points of division, and construct cylinders of revolution, as in Art. 160. The volume of any such cylinder will be $\pi y^2 \Delta x$ and its weight $W\pi y^2 \Delta x$, where W = weight of a cubic unit of the fluid. The work done in lifting this cylinder of the fluid out of the reservoir (through the height x) will be

$$W\pi y^2 x \Delta x.$$

[Work done in lifting equals the weight multiplied by the vertical height.]

The work done in lifting all such cylinders to the top is the sum

$$\sum_{i=1}^n W\pi y_i^2 x_i \Delta x_i.$$

The work done in emptying that part of the reservoir will evidently be the limit of this sum. Hence, by the Fundamental Theorem,

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n W\pi y_i^2 x_i \Delta x_i = \int W\pi y^2 x dx.$$

Therefore the work done in emptying a reservoir in the form of a solid of revolution from the depth a to the depth b is given by the formula

$$(F) \quad \text{Work} = W\pi \int_a^b y^2 x dx,$$

where the value of y in terms of x must be substituted from the equation of the revolved curve.

ILLUSTRATIVE EXAMPLE 1. Calculate the work done in pumping out the water filling a hemispherical reservoir 10 ft. deep.

Solution. The equation of the circle is

$$x^2 + y^2 = 100.$$

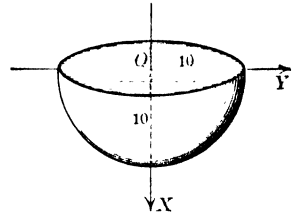
Hence $y^2 = 100 - x^2,$

$$W = 62,$$

and the limits are from $x = 0$ to $x = 10$.

Substituting in (F), we get

$$\text{Work} = 62 \pi \int_0^{10} (100 - x^2)x \, dx = 155,000 \pi \text{ ft.-lb.}$$



The essential principle in the above reasoning is that the element of work ($= dw$) done in lifting an elementary volume ($= dV$) through a height ($= h$) is

$$dw = Wh \, dV,$$

where W = weight of unit volume of the fluid. With this in mind, the axes of coördinates may be chosen in any convenient manner.

ILLUSTRATIVE EXAMPLE 2. A conical cistern is 20 ft. across the top and 15 ft. deep. If the surface of the water is 5 ft. below the top, find the work done in pumping the water to the top of the cistern.

Solution. Take axes OX and OY as in the figure. Then

$$dV = \pi x^2 \, dy,$$

$$h = 15 - y,$$

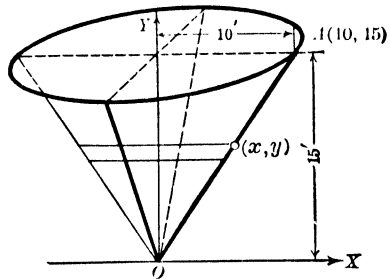
$$dw = W(15 - y)\pi x^2 \, dy.$$

The equation of the element OA is $x = \frac{2}{3}y$. Substituting,

$$dw = \pi W(15 - y)\left(\frac{2}{3}y\right)^2 dy = \frac{4}{9} \pi W(15y^2 - y^3) dy.$$

The limits are $y = 0$ and $y = 10$, since the water is 10 ft. deep. Integrating,

$$w = \frac{4}{9} \pi W \int_0^{10} (15y^2 - y^3) dy = 216,421 \text{ ft.-lb. Ans.}$$



Work done by an expanding gas. If a gas in a cylinder expands against a piston head from volume v_0 cu. ft. to v_1 cu. ft., the external work done in foot-pounds is

$$(G) \quad \text{Work} = \int_{v_0}^{v_1} p \, dv,$$

where p = pressure in pounds per square foot.

Proof. Let the volume increase from v to $v + dv$.

Let c = area of cross section of the cylinder.

Then $\frac{dv}{c}$ = distance the piston moves.

Since pc = force causing the expansion dv ,

$$\text{Element of work done} = pc \cdot \frac{dv}{c} = p dv.$$

Then (G) follows by the Fundamental Theorem. To use (G), the relation between p and v during the expansion must be known. This relation has the form

$$(1) \quad pv^n = \text{constant},$$

the exponent n being a constant.

Isothermal expansion occurs when the temperature remains constant. Then $n = 1$, and the pressure-volume relation is

$$(2) \quad pv = p_0v_0 = p_1v_1.$$

If a graph of (1) is made (*pressure-volume diagram*), plotting volumes as abscissas and pressures as ordinates, the area under this curve gives, numerically, the work done, as calculated by (G). In isothermal expansion the graph of (2) is a rectangular (equilateral) hyperbola.

PROBLEMS

1. A vertical cylindrical cistern of diameter 16 ft. and depth 20 ft. is full of water ($W = 62.5$). Calculate the work necessary to pump the water to the top of the cistern. *Ans.* $800,000 \pi$ ft. lb.

2. If the cistern of Problem 1 is half full, calculate the work necessary to pump the water to the top.

3. A conical cistern 20 ft. across the top and 20 ft. deep is full of water ($W = 62.5$). Calculate the work necessary to pump the water to a height of 15 ft. above the top of the cistern. *Ans.* $\frac{2,500,000 \pi}{3}$ ft. lb.

4. A hemispherical tank of diameter 10 ft. is full of oil weighing 60 lb. per cubic foot. Calculate the work necessary to pump the oil to the top of the tank. *Ans.* 9375π ft. lb.

5. A hemispherical tank of diameter 20 ft. is full of oil weighing 60 lb. per cubic foot. The oil is pumped to a height of 10 ft. above the top of the tank by an engine of $\frac{1}{2}$ H.P. (that is, the engine can do work at the rate of 16,500 ft. lb. per minute). How long will it take the engine to empty the tank?

6. Find the work done in pumping out a semi-elliptical reservoir full of water ($W = 62$). The top is a circle of diameter 6 ft., and the depth is 5 ft. *Ans.* $3487\frac{1}{2} \pi$ ft. lb.

7. A conical reservoir 12 ft. deep is filled with a liquid weighing 80 lb. per cubic foot. The top of the reservoir is a circle 8 ft. in diameter. Calculate the work necessary to pump the liquid to the top of the reservoir. *Ans.* $15,360 \pi$ ft. lb.

8. A water tank is in the form of a hemisphere, 24 ft. in diameter, surmounted by a cylinder of the same diameter and 10 ft. high. Find the work done in pumping it out when it is filled within 2 ft. of the top.

9. A bucket of weight M is to be lifted from the bottom of a shaft h ft. deep. The weight of the rope used to hoist it is m lb. per foot. Find the work done.

10. A quantity of air with an initial volume of 200 cu. ft. and pressure of 15 lb. per square inch is compressed to 80 lb. per square inch. Determine the final volume and the work done if the isothermal law holds, that is, $pv = C$. *Ans.* 37.5 cu. ft. ; 723,000 ft. lb.

11. Determine the final volume and work done in Problem 10 if the adiabatic law holds, that is $pv^n = C$, assuming $n = 1.4$.

Ans. 60 cu. ft. ; 648,000 ft. lb.

12. Air at pressure of 15 lb. per square inch is compressed from 200 cu. ft. to 50 cu. ft. Determine the final pressure and the work done if the law is $pv = C$. *Ans.* 60 lb. per square inch ; 599,000 ft. lb.

13. Solve Problem 12 if the law is $pv^n = C$, assuming $n = 1.4$.

Ans. 104.5 lb. per square inch ; 801,000 ft. lb.

14. A quantity of gas with an initial volume of 16 cu. ft. and pressure of 60 lb. per square inch expands until the pressure is 30 lb. per square inch. Determine the final volume and the work done by the gas if the law is $pv = C$. *Ans.* 32 cu. ft. ; 95,800 ft. lb.

15. Solve Problem 14 if the law is $pv^n = C$, assuming $n = 1.2$.

Ans. 28.5 cu. ft. ; 75,600 ft. lb.

16. A quantity of air with an initial volume of 200 cu. ft. and pressure of 15 lb. per square inch is compressed to 30 cu. ft. Determine the final pressure and the work done if the law is $pv = C$.

17. Solve Problem 16 if the law is $pv^n = C$, assuming $n = 1.4$.

18. A gas expands from an initial pressure of 80 lb. per square inch and volume of 2.5 cu. ft. to a volume of 9 cu. ft. Find the work done if the law is $pv^n = C$, assuming $n = 1.0646$.

19. Solve Problem 18 if $n = 1.131$.

20. Determine the amount of attraction exerted by a thin, straight, homogeneous rod of uniform thickness, of length l , and of mass M upon a material point P of mass m situated at a distance of a from one end of the rod in its line of direction.

Solution. Suppose the rod to be divided into equal infinitesimal portions (elements) of length dx .

$$\frac{M}{l} = \text{mass of a unit length of rod ;}$$

hence $\frac{M}{l} dx = \text{mass of any element.}$

Newton's law for measuring the attraction between any two masses is ,

$$\text{Force of attraction} = \frac{\text{product of masses}}{(\text{distance between them})^2};$$

therefore the force of attraction between the particle at P and an element of the rod is

$$\frac{M}{l} m dx, \quad \begin{array}{c} m \\ \vdots \\ P \end{array} \quad \begin{array}{c} \text{---} x \text{---} | dx \\ \text{---} a \text{---} \end{array} \quad \begin{array}{c} \text{---} l \text{---} \end{array}$$

which is then an *element of the force of attraction required*. The total attraction between the particle at P and the rod being the limit of the sum of all such elements between $x = 0$ and $x = l$, we have

$$\text{Force of attraction} = \int_0^l \frac{M}{l} m dx = \frac{Mm}{l} \int_0^l \frac{dx}{(x+a)^2} = + \frac{Mm}{a(a+l)}. \quad \text{Ans.}$$

21. Determine the amount of attraction in the last example if P lies in the perpendicular bisector of the rod at the distance a from it.

$$\text{Ans. } \frac{2mM}{a\sqrt{4a^2 + l^2}}.$$

22. A vessel in the form of a right circular cone is filled with water. If h is its height and r the radius of the base, what time will it require to empty itself through an orifice of area a at the vertex?

Solution. Neglecting all hurtful resistances, it is known that the velocity of discharge through an orifice is that acquired by a body falling freely from a height equal to the depth of the water. If, then, x denotes the depth of the water,

$$v = \sqrt{2gx}.$$

Denote by dQ the volume of water discharged in time dt , and by dx the corresponding fall of surface. The volume of water discharged through the orifice in a unit of time is

$$a\sqrt{2gx},$$

being measured as a right cylinder of area of base a and altitude $v (= \sqrt{2gx})$. Therefore in time dt

$$(1) \quad dQ = a\sqrt{2gx} dt.$$

Denoting by S the area of the surface of the water when the depth is x , we have, from geometry,

$$\frac{S}{\pi r^2} = \frac{x^2}{h^2}, \quad \text{or} \quad S = \frac{\pi r^2 x^2}{h^2}.$$

But the volume of water discharged in time dt may also be considered as the volume of a cylinder AB of area of base S and altitude dx ; hence

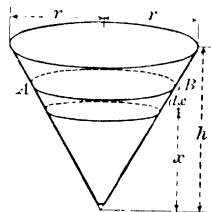
$$(2) \quad dQ = S dx = \frac{\pi r^2 x^2 dx}{h^2}.$$

Equating (1) and (2) and solving for dt ,

$$dt = \frac{\pi r^2 x^2 dx}{ah^2 \sqrt{2gx}}.$$

Therefore

$$t = \int_0^h \frac{\pi r^2 x^2 dx}{ah^2 \sqrt{2gx}} = \frac{2\pi r^2 \sqrt{h}}{5a\sqrt{2g}}. \quad \text{Ans.}$$



181. Mean value of a function. The *arithmetic mean* (or average value) of n numbers y_1, y_2, \dots, y_n , is

$$(1) \quad \bar{y} = \frac{1}{n} (y_1 + y_2 + \dots + y_n).$$

We proceed to establish the formula

$$(H) \text{ Mean value of } \phi(x) \left. \begin{array}{l} \text{from } x = a \text{ to } x = b \end{array} \right\} = \frac{\int_a^b \phi(x) dx}{b - a}.$$

The figure shows the graph of

$$(2) \quad y = \phi(x).$$

The mean value ($= \bar{y}$) of the ordinates of the arc PQ is to be defined. Divide AB into n equal parts each equal to Δx and let y_1, y_2, \dots, y_n , be the ordinates at the n points of division. Then (1) will give an approximate value for the mean value required. Multiply numerator and denominator of the right-hand member of (1) by Δx . Then, since $n \Delta x = b - a$, we get

$$(3) \quad \bar{y} \text{ (approximately)} = \frac{y_1 \Delta x + y_2 \Delta x + \dots + y_n \Delta x}{b - a}.$$

But the numerator in (3) is, approximately, the area $APRQB$. The average value of y (or $\phi(x)$) is defined as the limit of the right-hand member in (3) when $n \rightarrow \infty$. This gives (H).

In the figure the mean value of $\phi(x)$ equals CR if area rectangle $ABML = \text{area } ABQRP$.

Taking y as the function (dependent variable), then (H) becomes

$$(I) \quad \bar{y} = \frac{\int_a^b y dx}{b - a}.$$

ILLUSTRATIVE EXAMPLE. Given the circle

$$(4) \quad x^2 + y^2 = r^2.$$

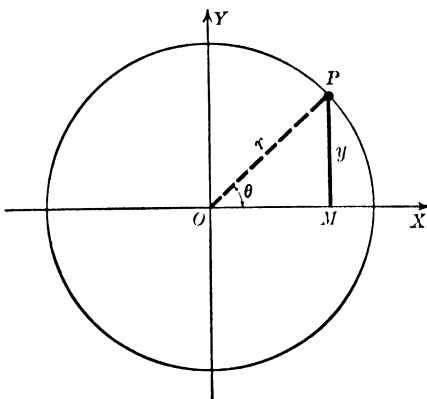
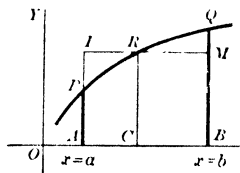
Find the average value of the ordinates in the first quadrant

(a) when y is expressed as a function of the abscissa x ;

(b) when y is expressed as a function of the angle $\theta = \angle MOP$.

Solution. (a) Since $y = \sqrt{r^2 - x^2}$, the numerator in (I) is

$$\int_0^r \sqrt{r^2 - x^2} dx = \frac{1}{4} \pi r^2. \text{ Then } \bar{y} = \frac{1}{4} \pi r = 0.785 r. \text{ Ans.}$$



(b) Since $y = r \sin \theta$, and the limits are $\theta = 0 = a$, $\theta = \frac{1}{2} \pi = b$, the numerator in (I) is

$$\int_0^{\frac{1}{2} \pi} r \sin \theta \, d\theta = r. \text{ Since } b - a = \frac{1}{2} \pi, \text{ we have } \bar{y} = \frac{2}{\pi} r = 0.637 r. \text{ Ans.}$$

Thus we have quite different values of y , depending upon the independent variable with respect to which the mean value is taken.

As shown in the above example, the average value of a given function y will depend upon the variable chosen as the independent variable. For this reason, we write (I) in the form

$$(5) \quad \bar{y}_x = \frac{\int_a^b y \, dx}{b - a},$$

in order to indicate explicitly the variable with respect to which y is averaged.

Thus, in the Illustrative Example, we have $\bar{y}_x = 0.785 r$, and $\bar{y}_\theta = 0.637 r$.

PROBLEMS

1. Find the average value of $y = x^2$ from $x = 0$ to $x = 10$. *Ans.* $33\frac{1}{3}$.
2. Find the average value of the ordinates of $y^2 = 4x$ from $(0, 0)$ to $(4, 4)$ taken uniformly along the x -axis. *Ans.* $2\frac{2}{3}$.
3. Find the average value of the abscissas of $y^2 = 4x$ from $(0, 0)$ to $(4, 4)$ when uniformly distributed along the y -axis. *Ans.* $1\frac{1}{3}$.
4. Find the average value of $\sin x$ between $x = 0$ and $x = \pi$. *Ans.* $\frac{2}{\pi}$.
5. Find the average value of $\sin^2 x$ between $x = 0$ and $x = \pi$. (This average value is frequently used in the theory of alternating currents.) *Ans.* $\frac{1}{2}$.

6. If a particle in a vacuum were thrown downward with an initial velocity of v_0 ft. per second, the velocity after t sec. would be given by

$$(1) \quad v = v_0 + gt.$$

The velocity after falling s ft. would be given by

$$(2) \quad v = \sqrt{v_0^2 + 2gs}. \quad (\text{Take } g = 32)$$

Find the average value of v

- (a) during the first 5 sec., starting from rest; *Ans.* 80 ft. per second.
- (b) during the first 5 sec., starting with an initial velocity of 36 ft. per second; *Ans.* 116 ft. per second.
- (c) during the first $2\frac{1}{2}$ sec., starting from rest; *Ans.* 40 ft. per second.
- (d) during the first 100 ft., starting from rest; *Ans.* $53\frac{1}{3}$ ft. per sec.
- (e) during the first 100 ft., starting with an initial velocity of 60 ft. per second. *Ans.* $81\frac{2}{3}$ ft. per second.

7. In simple harmonic motion $s = a \cos nt$. Find the average value of the velocity during one quarter of a period (a) as to the time; (b) as to the distance.

8. Show that in simple harmonic motion the average kinetic energy with respect to the time for any multiple of a quarter period is half the maximum kinetic energy.

9. A point is taken at random on a straight line of length a . Prove (a) that the average area of the rectangle whose sides are the two segments is $\frac{1}{6} a^2$; (b) that the average value of the sum of the squares on the two segments is $\frac{2}{3} a^2$.

10. If a point moves with constant acceleration, the average as to the time of the square of the velocity is $\frac{1}{3}(v_0^2 + v_0 v_1 + v_1^2)$, where v_0 is the initial and v_1 the final velocity.

11. Show that the average horizontal range of a particle projected with a given velocity at an arbitrary elevation is 0.6366 of the maximum horizontal range.

HINT. Take $\alpha = 0$ in the formula of Problem 35, p. 114.

The formulas

$$(6) \quad \bar{x}_s = \frac{\int x \, ds}{\int ds}, \quad \bar{y}_s = \frac{\int y \, ds}{\int ds},$$

where (x, y) is any point on a curve for which ds is the element of arc, define the *centroid of the arc*. They give, respectively, the average values of the abscissas and ordinates of points on the curve when distributed uniformly along it. (Compare Art. 177.)

12. Show that the area of the curved surface generated by revolving an arc of a plane curve about a line in its plane not cutting the arc equals the length of the arc times the circumference of the circle described by its centroid (6). (Theorem of Pappus. Compare Art. 250.)

HINT. Use (L), Art. 164.

13. Find the centroid of the arc of the parabola $y^2 = 4x$ from $(0, 0)$ to $(4, 4)$.
Ans. $\bar{x} = 1.64, \bar{y} = 2.29$.

14. Find the centroid of an arc of the circle $\rho = a$ between $-\theta$ and $+\theta$.
Ans. $\bar{x} = \frac{a \sin \theta}{\theta}$.

15. Find the centroid of the perimeter of the cardioid $\rho = a(1 + \cos \theta)$.
Ans. $\bar{x} = \frac{4}{3} a, \bar{y} = 0$.

16. Find by the Theorem of Pappus the centroid of the arc of the circle $x^2 + y^2 = r^2$ which lies in the first quadrant.
Ans. $\bar{x} = \bar{y} = \frac{2r}{\pi}$.

17. Find by the Theorem of Pappus the surface of the torus generated by revolving the circle $(x - b)^2 + y^2 = a^2$ ($b > a$) about the y -axis.

18. A rectangle is revolved about an axis which lies in its plane and is perpendicular to a diagonal at its extremity. Find the area of the surface generated.

ADDITIONAL PROBLEMS

1. An area is bounded by the lines $y = x^2$, $x + y = 6$, $y = 0$, and $x = 3$. Find its centroid. *Ans.* $\bar{x} = \frac{76}{37}$, $\bar{y} = \frac{281}{881}$.

2. The abscissa of the centroid of the area bounded by the curve $2y = x^2$ and a certain line through the origin is 1. Find the ordinate of the centroid. *Ans.* $\frac{3}{4}$.

3. Find the centroid of the area bounded by $y = x^n$ ($n > 0$), the x -axis, and $x = 1$. Discuss the locus of the centroid as n varies.

$$\text{Ans. } \bar{x} = \frac{n+1}{n+2}, \bar{y} = \frac{n+1}{2(n+1)}.$$

4. Find the equation of the locus of the centroid of the area bounded by the x -axis and the parabola $y = cx - x^2$ when c varies. *Ans.* $5y = 2x^2$.

5. Given the parabola $x^2 = 2py$ and any oblique line $y = mx + b$ meeting the parabola in the points A and B . Through C , the midpoint of AB , draw a line parallel to the axis of the curve meeting the parabola at D . Prove that (a) the tangent to the parabola at D is parallel to the line AB ; (b) the centroid of the area $ACBD$ lies on the line CD .

6. Let P be a point on the parabola $y = x^2$, and let C be the centroid of the area bounded by the parabola, the x -axis, and the ordinate through P . Find the position of P so that the angle OPC is a maximum.

$$\text{Ans. Ordinate} = \frac{5}{14}.$$

7. A cistern has the form of a solid generated by revolving about its vertical axis a parabolic segment cut off by a chord 8 ft. long, perpendicular to the axis and at a distance of 8 ft. from the vertex. The cistern is filled with water weighing 62.5 lb. per cubic foot. Find the amount of work required to pump over the top of the cistern one half the volume of water it contains.

$$\text{Ans. } 16,000(\sqrt{2} - 1) \frac{\pi}{3} = 6937 \text{ ft.-lb.}$$

8. A hemispherical cistern of radius r is full of water. Two men, A and B , are to pump it out, each doing half the work. If A starts first, what will be the depth d of the water when he has finished his share of the work?

$$\text{Ans. } \frac{d}{r} = 1 - \sqrt{\frac{2 - \sqrt{2}}{2}} = 0.459.$$

9. A tank in the shape of an inverted circular cone is full of water. Two men are to pump the water to the top of the tank, each doing half the work. When the first man has finished his share of the work, let z denote the ratio of the depth of water left in the tank to the original depth. Show that z is determined by the equation $6z^4 - 8z^3 + 1 = 0$. Calculate the value of z to two decimals. *Ans.* 0.61.

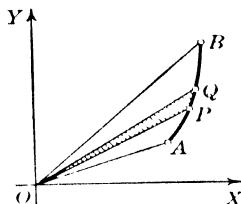
10. A well is 100 ft. deep. A bucket, weighing 3 lb., has a volume of 2 cu. ft. The bucket is filled with water at the bottom of the well and is then raised at a constant rate of 5 ft. per second to the top. Neglecting the weight of the rope, find the work done in raising the bucket if it is discovered that the water is leaking out at a constant rate of 0.01 cu. ft. per second. (A cubic foot of water weighs 62.4 lb.) *Ans.* 12,156 ft.-lb.

11. The area OAB is divided into elements such as OPQ by lines from O . Show that the area A and the moments of area M_x and M_y are given by

$$A = \frac{1}{2} \int (xy' - y) dx, \quad M_x = \frac{1}{3} \int y(xy' - y) dx,$$

$$M_y = \frac{1}{3} \int x(xy' - y) dx.$$

(The centroid of a triangle is on any median at two thirds of the distance from the vertex to the opposite side.)



12. Find the centroid of the hyperbolic sector bounded by the equilateral hyperbola $x = a \sec \theta$, $y = a \tan \theta$ and radii from the origin to the points $(a, 0)$ and (x, y) .

$$\text{Ans. } \bar{x} = \frac{2}{3} a \frac{\tan \theta}{\ln (\sec \theta + \tan \theta)}, \quad \bar{y} = \frac{2}{3} a \frac{\sec \theta - 1}{\ln (\sec \theta + \tan \theta)}.$$

CHAPTER XIX

SERIES

182. Definitions. A *sequence* is a succession of terms formed according to some fixed rule or law.

For example, $1, 4, 9, 16, 25$

and $1, -x, \frac{x^2}{2}, -\frac{x^3}{3}, \frac{x^4}{4}, -\frac{x^5}{5}$
are sequences.

A *series* is the indicated sum of the terms of a sequence. Thus from the above sequences we obtain the series

$$1 + 4 + 9 + 16 + 25$$

and $1 - x + \frac{x^2}{2} - \frac{x^3}{3} + \frac{x^4}{4} - \frac{x^5}{5}.$

When the number of terms is limited, the sequence or series is said to be *finite*. When the number of terms is unlimited, the sequence or series is called an *infinite sequence* or *infinite series*.

The *general term*, or *n*th term, is an expression which indicates the law of formation of the terms.

ILLUSTRATIVE EXAMPLE 1. In the first example given above, the general term, or *n*th term, is n^2 . The first term is obtained by setting $n = 1$, the tenth term by setting $n = 10$, etc.

ILLUSTRATIVE EXAMPLE 2. In the second example given above, the *n*th term, except for $n = 1$, is $\frac{(-x)^{n-1}}{n-1}$.

If the sequence is infinite, this fact is indicated by the use of dots, as

$$1, 4, 9, \dots, n^2, \dots$$

Factorial numbers. An expression which occurs frequently in connection with series is a product of successive integers, beginning with 1. Thus, $1 \times 2 \times 3 \times 4 \times 5$ is called *5 factorial* and is indicated by $\underline{5}$ or $5!$

In general, $\underline{n} = 1 \times 2 \times 3 \times \dots \times (n-1) \times n$

is called *n factorial*. It is understood that n is a positive integer. The expression \underline{n} has no meaning if n is not a positive integer.

183. The geometric series. For the geometric series of n terms,

$$(1) \quad S_n = a + ar + ar^2 + \cdots + ar^{n-1},$$

it is shown in elementary algebra that

$$(2) \quad S_n = \frac{a(1-r^n)}{1-r}, \quad \text{or} \quad S_n = \frac{a(r^n-1)}{r-1},$$

the first form being generally used if $|r| < 1$, and the second form if $|r| > 1$.

If $|r| < 1$, then r^n decreases in numerical value as n increases and

$$\lim_{n \rightarrow \infty} (r^n) = 0.$$

From formula (2) we see, therefore, that (Art. 16)

$$(3) \quad \lim_{n \rightarrow \infty} S_n = \frac{a}{1-r}.$$

Hence if $|r| < 1$ the sum S_n of a geometric series approaches a limit as the number of terms is increased indefinitely. In this case the series is said to be **convergent**.

If $|r| > 1$, then r^n will become infinite as n increases indefinitely (Art. 18). Hence, from the second formula in (2), the sum S_n will become infinite. In this case the series is said to be **divergent**.

A peculiar situation presents itself if $r = -1$. The series then becomes

$$(4) \quad a - a + a - a + a - a \cdots.$$

If n is even the sum is zero. If n is odd the sum is a . As n increases indefinitely the sum does not increase indefinitely and it does not approach a limit. Such a series is called an **oscillating series**.

ILLUSTRATIVE EXAMPLE. Consider the geometric series with

$$(5) \quad a = 1, \quad r = \frac{1}{2},$$

$$S_n = 1 + \frac{1}{2} + \frac{1}{4} + \cdots + \frac{1}{2^{n-1}}.$$

We find, by (2), that
$$S_n = \frac{1 - \frac{1}{2^n}}{1 - \frac{1}{2}} = 2 - \frac{1}{2^{n-1}}.$$

Then

$$(6) \quad \lim_{n \rightarrow \infty} S_n = 2, \text{ which agrees with (3), when } a = 1, r = \frac{1}{2}.$$

It is interesting to discuss (5) geometrically. To do this, lay off successive values of S_n on a straight line, as in the figure.

n	1	2	3	4,	etc.
S_n	1	$1\frac{1}{2}$	$1\frac{3}{4}$	$1\frac{7}{8}$,	etc.

Each point thus determined bisects the segment between the preceding point and the point 2. Hence (6) is obvious.

PROBLEMS

In each of the following series (a) discover by inspection the law of formation; (b) write three more terms; (c) find the n th, or *general*, term.

1. $2 + 4 + 8 + 16 + \dots$

Ans. n th term $= 2^n$.

2. $1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \dots$

$$\frac{(-1)^{n-1}}{n}.$$

3. $-\frac{1}{2} + 0 + \frac{1}{4} + \frac{2}{6} + \frac{3}{6} + \dots$

$$\frac{n-2}{n+1}.$$

4. $x + \frac{x^2}{1} + \frac{x^3}{1 \cdot 2} + \frac{x^4}{1 \cdot 2 \cdot 3} + \dots$

$$\frac{nx^n}{[n]}.$$

5. $\frac{\sqrt{x}}{2} + \frac{x}{2 \cdot 4} + \frac{x \sqrt{x}}{2 \cdot 4 \cdot 6} + \frac{x^2}{2 \cdot 4 \cdot 6 \cdot 8} + \dots$

$$\frac{x^{\frac{n}{2}}}{2^n [n]}.$$

6. $\frac{a^2}{3} - \frac{a^3}{5} + \frac{a^4}{7} - \frac{a^5}{9} + \dots$

$$\frac{(-a)^{n+1}}{2n+1}.$$

Write the first four terms of the series whose n th, or *general*, term is given below.

7. $\frac{2^{n-1}}{\sqrt{n}}.$

Ans. $1 + \frac{2}{\sqrt{2}} + \frac{4}{\sqrt{3}} + \frac{8}{\sqrt{4}} + \dots$

8. $\frac{n+2}{2n-1}.$

$$3 + \frac{4}{3} + \frac{5}{5} + \frac{6}{7} + \dots$$

9. $\frac{n}{3^{n-1}}.$

$$1 + \frac{2}{3} + \frac{3}{9} + \frac{4}{27} + \dots$$

10. $\frac{x^{n-1}}{\sqrt{n}}.$

$$1 + \frac{x}{\sqrt{2}} + \frac{x^2}{\sqrt{3}} + \frac{x^3}{\sqrt{4}} + \dots$$

11. $\frac{(-1)^{n-1}x^{2n-1}}{[2n-1]}.$

$$x - \frac{x^3}{[3]} + \frac{x^5}{[5]} - \frac{x^7}{[7]} + \dots$$

12. $\frac{(x-a)^{n-1}}{[n]}.$

13. $\frac{(y+n)^{2n-1}}{2^n [n]}.$

14. $\frac{2^{\frac{n+1}{2}}}{\sqrt{n+2}}.$

15. $\frac{3^{n-1}\theta^n}{2^n [n-1]}.$

184. Convergent and divergent series. In the series

$$S_n = u_1 + u_2 + u_3 + \dots + u_n,$$

the variable S_n is a function of n . If we now let the number of terms ($= n$) increase without limit, one of two things may happen.

CASE I. S_n approaches a limit, say u , indicated by

$$(1) \quad \lim_{n \rightarrow \infty} S_n = u.$$

The infinite series is now said to be *convergent* and to converge to the value u , or to have the value u .

CASE II. S_n approaches no limit. The infinite series is now said to be *divergent*.

Examples of divergent series are

$$\begin{aligned} 1 + 2 + 3 + 4 + 5 + \cdots, \\ 1 - 1 + 1 - 1 + \cdots. \end{aligned}$$

As stated above, in a convergent series the *value of the series* is the number u (sometimes called the sum) defined by (1). No value is assigned to a divergent series.

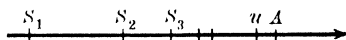
In the applications of infinite series, convergent series are of major importance. Thus it is essential to have means of testing a given series for convergence or divergence.

185. General theorems. Before developing special methods for testing series, attention is called to the following theorems, of which proofs are omitted.

Theorem I. *If S_n is a variable that always increases as n increases but never exceeds some definite fixed number A , then as n increases without limit, S_n will approach a limit u which is not greater than A .*

The figure illustrates the statement. The points determined by the values S_1, S_2, S_3 , etc. approach the point u , where

$$\lim_{n \rightarrow \infty} S_n = u,$$



and u is less than or equal to A .

ILLUSTRATIVE EXAMPLE. Show that the infinite series

$$(1) \quad 1 + 1 + \frac{1}{1 \cdot 2} + \frac{1}{1 \cdot 2 \cdot 3} + \cdots + \frac{1}{n} + \cdots$$

is convergent.

Solution. Neglect the first term, and write

$$(2) \quad S_n = 1 + \frac{1}{1 \cdot 2} + \frac{1}{1 \cdot 2 \cdot 3} + \cdots + \frac{1}{1 \cdot 2 \cdot 3 \cdots n}.$$

Consider the variable s_n defined by

$$(3) \quad s_n = 1 + \frac{1}{2} + \frac{1}{2 \cdot 2} + \cdots + \frac{1}{2^{n-1}},$$

in which we have replaced all integers in the denominators of (2), except 1, by 2. Obviously $S_n < s_n$. Also, in (3) we have a geometric series with $r = \frac{1}{2}$ and $s_n < 2$ no matter how large n may be (see Art. 183). Hence S_n as defined by (2) is a variable which always increases as n increases but remains less than 2. Hence S_n approaches a limit as n becomes infinite, and this limit is less than 2. Therefore the infinite series (1) is convergent, and its value is less than 3.

We shall see later that the value of (1) is the constant $e = 2.71828 \cdots$, the natural base (Art. 61).

Theorem II. *If S_n is a variable that always decreases as n increases but is never less than some definite fixed number B , then as n increases without limit, S_n will approach a limit which is not less than B .*

Consider now a convergent series

$$S_n = u_1 + u_2 + u_3 + \cdots + u_n$$

for which $\lim_{n \rightarrow \infty} S_n = u$.

Let the points determined by the values S_1, S_2, S_3 , etc. be plotted on a directed line. Then these points, as n increases, will approach the point determined by u (terms in S_n all of the same sign) or cluster about this point. Thus it is evident that

$$(A) \quad \lim_{n \rightarrow \infty} u_n = 0.$$

That is, in a convergent series, the terms must approach zero as a limit.

On the other hand, if the general (or n th) term of a series does not approach zero as n becomes infinite, we know at once that the series is divergent.

(A) is not, however, a sufficient condition for convergence; that is, even if the n th term does approach zero, we cannot state positively that the series is convergent. For, consider the harmonic series

$$1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots + \frac{1}{n}.$$

$$\text{Here} \quad \lim_{n \rightarrow \infty} (u_n) = \lim_{n \rightarrow \infty} \left(\frac{1}{n} \right) = 0;$$

that is, condition (A) is fulfilled. Yet we shall show in Art. 186 that the series is divergent.

We shall now proceed to deduce special tests which, as a rule, are easier to apply than the above theorems.

186. Comparison tests. In many cases it is easy to determine whether or not a given series is convergent by comparing it term by term with another series whose character is known.

Test for convergence. *Let*

$$(1) \quad u_1 + u_2 + u_3 + \cdots$$

be a series of positive terms which it is desired to test for convergence. If a series of positive terms already known to be convergent, namely,

$$(2) \quad a_1 + a_2 + a_3 + \cdots,$$

can be found whose terms are never less than the corresponding terms in the series (1) to be tested, then (1) is a convergent series and its value does not exceed that of (2).

Proof. Let $s_n = u_1 + u_2 + u_3 + \cdots + u_n$,
 and $S_n = a_1 + a_2 + a_3 + \cdots + a_n$,
 and suppose that $\lim_{n \rightarrow \infty} S_n = A$.

Then, since $S_n < A$ and $s_n \leq S_n$,
 it follows that $s_n < A$. Hence, by Theorem I, Art. 185, s_n approaches
 a limit and the series (1) is convergent and its value is not greater
 than A .

ILLUSTRATIVE EXAMPLE 1. Test the series

$$(3) \quad 1 + \frac{1}{2^2} + \frac{1}{3^3} + \frac{1}{4^4} + \frac{1}{5^5} + \cdots.$$

Solution. Compare with the geometric series

$$(4) \quad 1 + \frac{1}{2} + \frac{1}{2^2} + \frac{1}{2^3} + \frac{1}{2^4} + \cdots,$$

which is known to be convergent. The terms of (4) are never less than the corresponding terms of (3). Hence (3) also is convergent.

Following a line of reasoning similar to that applied to (1) and (2),
 we may prove the

Test for divergence. *Let*

$$(5) \quad u_1 + u_2 + u_3 + \cdots$$

*be a series of positive terms to be tested, which are never less than the
 corresponding terms of a series of positive terms, namely,*

$$(6) \quad b_1 + b_2 + b_3 + \cdots,$$

known to be divergent. Then (5) is a divergent series.

ILLUSTRATIVE EXAMPLE 2. Show that the harmonic series

$$(7) \quad 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots$$

is divergent.

Solution. Rewrite (7) as below and compare with the series written under it.
 The square brackets are introduced to aid in the comparison.

$$(8) \quad 1 + \frac{1}{2} + \left[\frac{1}{3} + \frac{1}{4} \right] + \left[\frac{1}{5} + \frac{1}{6} + \frac{1}{7} + \frac{1}{8} \right] + \left[\frac{1}{9} + \cdots + \frac{1}{16} \right] + \cdots.$$

$$(9) \quad \frac{1}{2} + \frac{1}{2} + \left[\frac{1}{3} + \frac{1}{3} \right] + \left[\frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4} \right] + \left[\frac{1}{5} + \cdots + \frac{1}{16} \right] + \cdots.$$

We observe the following facts. The terms in (8) are never less than the
 corresponding terms in (9).

But (9) is divergent. For the sum of the terms in each square bracket is $\frac{1}{2}$,
 and S_n will increase indefinitely as n becomes infinite.

Hence (8) is divergent.

ILLUSTRATIVE EXAMPLE 3. Test the series

$$1 + \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{3}} + \frac{1}{\sqrt{4}} + \cdots$$

Solution. This series is divergent, since its terms are greater than the corresponding terms of the harmonic series (7) which is divergent.

The " p series,"

$$(10) \quad 1 + \frac{1}{2^p} + \frac{1}{3^p} + \frac{1}{4^p} + \cdots + \frac{1}{n^p} + \cdots,$$

is useful in applying the comparison test.

Theorem. The p series is convergent when $p > 1$, and divergent for other values of p .

Proof. Rewrite (10) as below and compare with the series written under it. The square brackets are used to aid in the comparison.

$$(11) \quad 1 + \left[\frac{1}{2^p} + \frac{1}{3^p} \right] + \left[\frac{1}{4^p} + \frac{1}{5^p} + \frac{1}{6^p} + \frac{1}{7^p} \right] + \left[\frac{1}{8^p} + \cdots + \frac{1}{15^p} \right] + \cdots.$$

$$(12) \quad 1 + \left[\frac{1}{2^p} + \frac{1}{2^p} \right] + \left[\frac{1}{4^p} + \frac{1}{4^p} + \frac{1}{4^p} + \frac{1}{4^p} \right] + \left[\frac{1}{8^p} + \cdots + \frac{1}{8^p} \right] + \cdots.$$

If $p > 1$, the terms in (12) are never less than the corresponding terms in (11). But, in (12), the sums within the brackets are

$$\frac{1}{2^p} + \frac{1}{2^p} = \frac{2}{2^p} = \frac{1}{2^{p-1}}; \quad \frac{1}{4^p} + \frac{1}{4^p} + \frac{1}{4^p} + \frac{1}{4^p} = \frac{4}{4^p} = \frac{2^2}{2^{2p}} = \frac{1}{2^{2(p-1)}};$$

$$\frac{1}{8^p} + \cdots + \frac{1}{8^p} = \frac{8}{8^p} = \frac{2^3}{2^{3p}} = \frac{1}{2^{3(p-1)}},$$

and so on. Hence, to test (12) for convergence, we may consider the series

$$(13) \quad 1 + \frac{1}{2^{p-1}} + \left(\frac{1}{2^{p-1}} \right)^2 + \left(\frac{1}{2^{p-1}} \right)^3 + \cdots.$$

When $p > 1$, series (13) is a geometric series with the common ratio less than unity, and is therefore convergent. Therefore (10) is also convergent. When $p = 1$, series (10) is the harmonic series and is divergent. When $p < 1$, the terms of series (10) will, after the first, be greater than the corresponding terms of the harmonic series; hence (10) is now divergent. Q.E.D.

ILLUSTRATIVE EXAMPLE 4. Show that the series

$$(14) \quad \frac{2}{2 \cdot 3 \cdot 4} + \frac{4}{3 \cdot 4 \cdot 5} + \frac{6}{4 \cdot 5 \cdot 6} + \cdots + \frac{2n}{(n+1)(n+2)(n+3)} + \cdots$$

is convergent.

Solution. In (14), $u_n < \frac{2n}{n^3}$, or $\frac{1}{2}u_n < \frac{1}{n^2}$;

that is, $\frac{1}{2}u_n$ is less than the general term of the p series when $p = 2$. Hence the series each of whose terms is half the corresponding term in (14) is convergent and therefore (14) also is convergent.

PROBLEMS

Test each of the following series.

1. $\frac{1}{1} + \frac{1}{\sqrt{2^3}} + \frac{1}{\sqrt{3^3}} + \cdots \frac{1}{\sqrt{n^3}} + \cdots$. Ans. Convergent.
2. $\frac{1}{1} + \frac{1}{\sqrt[3]{2}} + \frac{1}{\sqrt[3]{3}} + \cdots \frac{1}{\sqrt[3]{n}} + \cdots$. Divergent.
3. $\frac{2}{1} + \frac{2}{2^2} + \frac{2}{3^3} + \cdots \frac{2}{n^n} + \cdots$. Convergent.
4. $\frac{3}{1 \cdot 2} + \frac{3}{2 \cdot 3} + \frac{3}{3 \cdot 4} + \cdots \frac{3}{n(n+1)} + \cdots$. Convergent.
5. $\frac{4}{2 \cdot 3} + \frac{8}{3 \cdot 4} + \frac{12}{4 \cdot 5} + \cdots \frac{4n}{(n+1)(n+2)} + \cdots$. Divergent.
6. $\frac{3}{2 \cdot 3 \cdot 4} + \frac{5}{3 \cdot 4 \cdot 5} + \frac{7}{4 \cdot 5 \cdot 6} + \cdots \frac{2n+1}{(n+1)(n+2)(n+3)} + \cdots$. Convergent.
7. $\frac{1}{5} + \frac{1}{10} + \frac{1}{15} + \cdots \frac{1}{5n} + \cdots$. Divergent.
8. $\frac{1}{4} + \frac{1}{5} + \frac{1}{6} + \cdots \frac{1}{n+3} + \cdots$. Divergent.
9. $\frac{1}{4} + \frac{1}{10} + \frac{1}{28} + \cdots \frac{1}{3^n+1} + \cdots$. Convergent.
10. $\frac{1}{3} + \frac{1}{\sqrt{3}} + \frac{1}{\sqrt[3]{3}} + \cdots \frac{1}{\sqrt[n]{3}} + \cdots$. Divergent.
11. $\frac{1}{4} + \frac{1}{7} + \frac{1}{12} + \cdots \frac{1}{n^2+3} + \cdots$. Convergent.
12. $\frac{1}{2} + \frac{1}{8} + \frac{1}{26} + \cdots \frac{1}{3^n-1} + \cdots$. Convergent.
13. $\frac{1}{2 \cdot 2 \cdot 3} + \frac{2}{2 \cdot 3 \cdot 4} + \frac{3}{2 \cdot 4 \cdot 5} + \cdots \frac{n}{2(n+1)(n+2)} + \cdots$. Divergent.
14. $1 + \frac{1}{2} + \frac{1}{6} + \frac{1}{12} + \frac{1}{20} + \frac{1}{30} + \frac{1}{42} + \cdots$. Convergent.
15. $\frac{2}{9} + \frac{2^2}{28} + \frac{2^3}{65} + \frac{2^4}{126} + \cdots$. 17. $\frac{1}{\log 2} + \frac{1}{\log 3} + \frac{1}{\log 4} + \cdots$.
16. $\frac{2}{3} + \frac{2}{6} + \frac{2}{9} + \frac{1}{12} + \cdots$. 18. $\frac{1}{2} + \frac{1}{6} + \frac{1}{16} + \frac{1}{34} + \cdots$.

187. Cauchy's test-ratio test. In the infinite geometric series

$$a + ar + ar^2 + \cdots + ar^n + ar^{n+1} + \cdots,$$

the ratio of the consecutive general terms ar^n and ar^{n+1} is the common ratio r . Moreover, we know that the series is convergent when $|r| < 1$ and divergent for other values. We now explain a ratio test which may be applied to any series.

Theorem. *Let*

$$(1) \quad u_1 + u_2 + u_3 + \cdots + u_n + u_{n+1} + \cdots$$

be an infinite series of positive terms. Consider consecutive general terms u_n and u_{n+1} , and form the test ratio.

$$\text{Test ratio} = \frac{u_{n+1}}{u_n}.$$

Find the limit of this test ratio when n becomes infinite. Let this be

$$\rho = \lim_{n \rightarrow \infty} \frac{u_{n+1}}{u_n}.$$

- I. When $\rho < 1$, the series is convergent.
- II. When $\rho > 1$, the series is divergent.
- III. When $\rho = 1$, the test fails.

Proof. I. When $\rho < 1$. By the definition of a limit (Art. 14) we can choose n so large, say $n = m$, that when $n \geq m$ the ratio $\frac{u_{n+1}}{u_n}$ will differ from ρ by as little as we please, and therefore be less than a proper fraction r . Hence

$$u_{m+1} < u_m r; \quad u_{m+2} < u_{m+1} r < u_m r^2; \quad u_{m+3} < u_m r^3;$$

and so on. Therefore, after the term u_m , each term of the series (1) is less than the corresponding term of the geometric series

$$(2) \quad u_m r + u_m r^2 + u_m r^3 + \cdots.$$

But since $r < 1$, the series (2), and therefore also the series (1), is convergent (Art. 186).

II. When $\rho > 1$ (or $\rho = \infty$). Following the same line of reasoning as in I, the series (1) may be shown to be divergent.

III. When $\rho = 1$, the series may be either convergent or divergent; that is, the test fails. For, consider the p series, namely,

$$1 + \frac{1}{2^p} + \frac{1}{3^p} + \frac{1}{4^p} + \cdots + \frac{1}{n^p} + \frac{1}{(n+1)^p} + \cdots.$$

$$\text{The test ratio is } \frac{u_{n+1}}{u_n} = \left(\frac{n}{n+1}\right)^p = \left(1 - \frac{1}{n+1}\right)^p;$$

$$\text{and } \lim_{n \rightarrow \infty} \left(\frac{u_{n+1}}{u_n}\right) = \lim_{n \rightarrow \infty} \left(1 - \frac{1}{n+1}\right)^p = (1)^p = 1 (= \rho).$$

Hence $\rho = 1$, no matter what value p may have. But in Art. 186 we showed that

- when $p > 1$, the series converges, and
- when $p \leq 1$, the series diverges.

Thus it appears that ρ can equal unity both for convergent and for divergent series. There are other tests to apply in cases like this, but the scope of our book does not admit of their consideration.

For convergence it is not enough that the test ratio is less than unity for all values of n . This test requires that the *limit* of the test ratio shall be less than unity. For instance, in the harmonic series the test ratio is always less than unity. The *limit*, however, equals unity.

The rejection of a group of terms at the beginning of a series will affect the *value* but not the *existence* of the limit.

188. Alternating series. This is the name given to a series whose terms are alternately positive and negative.

Theorem. If $u_1 - u_2 + u_3 - u_4 + \cdots$

is an alternating series in which each term is numerically less than the one which precedes it, and if $\lim_{n \rightarrow \infty} u_n = 0$,

then the series is convergent.

Proof. When n is even, S_n may be written in the two forms

$$(1) \quad S_n = (u_1 - u_2) + (u_3 - u_4) + \cdots + (u_{n-1} - u_n),$$

$$(2) \quad S_n = u_1 - (u_2 - u_3) - \cdots - (u_{n-2} - u_{n-1}) - u_n.$$

Each expression in parentheses is positive. Hence when n increases through even values, (1) shows that S_n increases and (2) shows that S_n is always less than u_1 ; therefore, by Theorem I, Art. 185, S_n approaches a limit l . But S_{n+1} also approaches this limit l , since $S_{n+1} = S_n + u_{n+1}$ and $\lim_{n \rightarrow \infty} u_{n+1} = 0$. Hence when n increases through all integral values, $S_n \rightarrow l$ and the series is convergent.

ILLUSTRATIVE EXAMPLE. Test the alternating series $1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \cdots$.

Solution. Each term is less in numerical value than the preceding one, and $u_n = \frac{1}{n}$. Hence $\lim_{n \rightarrow \infty} (u_n) = 0$, and the series is convergent.

An important consequence of the above proof is the statement:

The error made by breaking a convergent alternating series off at any term does not exceed numerically the value of the first of the terms discarded.

Thus, the sum of ten terms in the above Illustrative Example is 0.646, and the value of the series differs from this by less than one eleventh.

In the above statement it is assumed, however, that the series has been carried far enough so that the terms are decreasing numerically.

189. Absolute convergence. A series is said to be *absolutely* or *unconditionally* convergent when the series formed from it by making all its terms positive is convergent. Other convergent series are said to be *conditionally convergent*.

For example, the series $1 - \frac{1}{2^2} + \frac{1}{3^3} - \frac{1}{4^4} + \frac{1}{5^5} - \dots$

is *absolutely convergent*, since the series (3), Art. 186, is convergent. The alternating series

$$1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \dots$$

is *conditionally convergent*, since the harmonic series is divergent.

A series with some positive and some negative terms is convergent if the series deduced from it by making all the signs positive is convergent.

The proof of this theorem is omitted.

190. Summary. Assuming that the test-ratio test of Art. 187 holds without placing any restriction on the signs of the terms, we may summarize our results in the following

General directions for testing the series

$$u_1 + u_2 + u_3 + u_4 + \dots + u_n + u_{n+1} + \dots$$

When it is an alternating series whose terms never increase in numerical value, and if

$$\lim_{n \rightarrow \infty} u_n = 0,$$

then the series is convergent.

In any series in which the above conditions are not satisfied, we determine the form of u_n and u_{n+1} , form the test ratio, and calculate

$$\lim_{n \rightarrow \infty} \left(\frac{u_{n+1}}{u_n} \right) = \rho.$$

I. When $|\rho| < 1$, the series is absolutely convergent.

II. When $|\rho| > 1$, the series is divergent.

III. When $|\rho| = 1$, the test fails, and we compare the series with some series which we know to be convergent, as

$$a + ar + ar^2 + ar^3 + \dots; \quad (r < 1) \text{ (geometric series)}$$

$$1 + \frac{1}{2^p} + \frac{1}{3^p} + \frac{1}{4^p} + \dots; \quad (p > 1) \text{ (p series)}$$

or compare the given series with some series which is known to be divergent, as

$$1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \dots; \quad \text{(harmonic series)}$$

$$1 + \frac{1}{2^p} + \frac{1}{3^p} + \frac{1}{4^p} + \dots \quad (p < 1) \text{ (p series)}$$

ILLUSTRATIVE EXAMPLE 1. Test the series

$$1 + \frac{1}{\boxed{1}} + \frac{1}{\boxed{2}} + \frac{1}{\boxed{3}} + \frac{1}{\boxed{4}} + \cdots.$$

Solution. Here

$$u_n = \frac{1}{\boxed{n-1}}, \quad u_{n+1} = \frac{1}{\boxed{n}}.$$

$$\frac{u_{n+1}}{u_n} = \frac{\boxed{n-1}}{\boxed{n}} = \frac{1}{n}.$$

$$\rho = \lim_{n \rightarrow \infty} \frac{1}{n} = 0,$$

and the series is convergent.

ILLUSTRATIVE EXAMPLE 2. Test the series

$$\frac{\boxed{1}}{10} + \frac{\boxed{2}}{10^2} + \frac{\boxed{3}}{10^3} + \cdots.$$

Solution. Here

$$u_n = \frac{\boxed{n}}{10^n}, \quad u_{n+1} = \frac{\boxed{n+1}}{10^{n+1}}.$$

$$\frac{u_{n+1}}{u_n} = \frac{\boxed{n+1}}{10^{n+1}} \cdot \frac{10^n}{\boxed{n}} = \frac{n+1}{10}.$$

$$\rho = \lim_{n \rightarrow \infty} \frac{n+1}{10} = \infty,$$

and the series is divergent.

ILLUSTRATIVE EXAMPLE 3. Test the series

$$\frac{1}{1 \cdot 2} + \frac{1}{3 \cdot 4} + \frac{1}{5 \cdot 6} + \cdots.$$

Solution. Here $u_n = \frac{1}{(2n-1)2n}, \quad u_{n+1} = \frac{1}{(2n+1)(2n+2)}.$

$$\frac{u_{n+1}}{u_n} = \frac{(2n-1)2n}{(2n+1)(2n+2)} = \frac{4n^2 - 2n}{4n^2 + 6n + 2}.$$

$$\rho = \lim_{n \rightarrow \infty} \frac{4n^2 - 2n}{4n^2 + 6n + 2} = 1,$$

by the rule in Art. 18. Hence the test-ratio test fails.

But if we compare the given series with the p series, when $p = 2$, namely,

$$1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \cdots,$$

we see that it must be convergent, since its terms are less than the corresponding terms of this p series, which was proved convergent.

PROBLEMS

Test each of the following series.

1. $\frac{3}{4} + 2\left(\frac{3}{4}\right)^2 + 3\left(\frac{3}{4}\right)^3 + 4\left(\frac{3}{4}\right)^4 + \cdots.$

Ans. Convergent.

2. $\frac{3}{2} + \frac{4}{2^2} + \frac{5}{2^3} + \frac{6}{2^4} + \cdots.$

Convergent.

3. $\frac{3}{2} + \frac{3^2}{2 \cdot 2^2} + \frac{3^3}{3 \cdot 2^3} + \frac{3^4}{4 \cdot 2^4} + \dots$ Ans. Divergent.
4. $\frac{1}{3} + \frac{1 \cdot 2}{3 \cdot 5} + \frac{1 \cdot 2 \cdot 3}{3 \cdot 5 \cdot 7} + \dots \frac{[n]}{3 \cdot 5 \cdot 7 \dots (2n+1)} + \dots$ Convergent.
5. $\frac{1}{1} + \frac{1 \cdot 3}{1 \cdot 4} + \frac{1 \cdot 3 \cdot 5}{1 \cdot 4 \cdot 7} + \dots \frac{1 \cdot 3 \cdot 5 \dots (2n-1)}{1 \cdot 4 \cdot 7 \dots (3n-2)} \dots$ Convergent.
6. $\frac{1}{1} + \frac{1 \cdot 2}{1 \cdot 3} + \frac{1 \cdot 2 \cdot 3}{1 \cdot 3 \cdot 5} + \frac{1 \cdot 2 \cdot 3 \cdot 4}{1 \cdot 3 \cdot 5 \cdot 7} + \dots$ Convergent.
7. $\frac{5}{1} + \frac{5^2}{[2]} + \frac{5^3}{[3]} + \frac{5^4}{[4]} + \dots$ Convergent.
8. $\frac{1}{9} + \frac{[2]}{9^2} + \frac{[3]}{9^3} + \frac{[4]}{9^4} + \dots$ Divergent.
9. $\frac{1}{3} + \frac{3}{3^2} + \frac{5}{3^3} + \frac{7}{3^4} + \dots$ 11. $\frac{1}{4 \cdot 3} + \frac{1}{5 \cdot 3^2} + \frac{1}{6 \cdot 3^3} + \frac{1}{7 \cdot 3^4} + \dots$
10. $1 + \frac{2[2]}{5} + \frac{2^2[3]}{10} + \frac{2^3[4]}{17} + \dots$ 12. $\frac{3}{5} + \frac{4}{5^2} + \frac{5}{5^3} + \frac{6}{5^4} + \dots$
13. $\frac{1}{3} + \frac{1 \cdot 3}{3 \cdot 6} + \frac{1 \cdot 3 \cdot 5}{3 \cdot 6 \cdot 9} + \frac{1 \cdot 3 \cdot 5 \cdot 7}{3 \cdot 6 \cdot 9 \cdot 12} + \dots$

191. Power series. A series whose terms are monomials in ascending positive integral powers of a variable, say x , of the form

$$(1) \quad a_0 + a_1x + a_2x^2 + a_3x^3 + \dots,$$

where the coefficients a_0, a_1, a_2, \dots are independent of x , is called a *power series in x* . Such series are of prime importance in the study of calculus.

A power series in x may converge for all values of x , or for no value except $x = 0$; or it may converge for some values of x different from 0 and be divergent for other values.

We shall examine (1) only for the case when the coefficients are such that

$$\lim_{n \rightarrow \infty} \left(\frac{a_{n+1}}{a_n} \right) = L,$$

where L is a definite number. To see the reason for this, form the test ratio (Art. 187) for (1), omitting the first term. Then we have

$$\frac{u_{n+1}}{u_n} = \frac{a_{n+1}x^{n+1}}{a_nx^n} = \frac{a_{n+1}}{a_n}x.$$

Hence for any fixed value of x ,

$$\rho = \lim_{n \rightarrow \infty} \left(\frac{a_{n+1}}{a_n} x \right) = x \lim_{n \rightarrow \infty} \left(\frac{a_{n+1}}{a_n} \right) = xL.$$

We have two cases:

I. If $L = 0$, the series (1) will converge for all values of x , since $\rho = 0$.

II. If L is not zero, the series will converge when $xL(= \rho)$ is numerically less than 1, that is, when x lies in the interval

$$-\frac{1}{|L|} < x < \frac{1}{|L|},$$

and will diverge for values of x outside this interval.

The end points of the interval, called the *interval of convergence*, must be examined separately. In any given series the test ratio should be formed and the interval of convergence determined by Art. 187.

ILLUSTRATIVE EXAMPLE 1. Find the interval of convergence for the series

$$(2) \quad x - \frac{x^2}{2^2} + \frac{x^3}{3^2} - \frac{x^4}{4^2} + \cdots.$$

Solution. The test ratio here is

$$\frac{u_{n+1}}{u_n} = -\frac{n^2}{(n+1)^2}x. \text{ Also, } \lim_{n \rightarrow \infty} \frac{n^2}{(n+1)^2} = 1,$$

by Art. 18. Hence $\rho = -x$, and the series converges when x is numerically less than 1 and diverges when x is numerically greater than 1.

Now examine the end points. Substituting $x = 1$ in (2), we get

$$1 - \frac{1}{2^2} + \frac{1}{3^2} - \frac{1}{4^2} + \cdots,$$

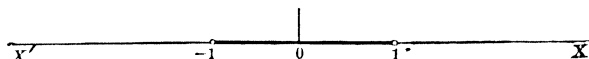
which is an alternating series that converges.

Substituting $x = -1$ in (2), we get

$$-1 - \frac{1}{2^2} - \frac{1}{3^2} - \frac{1}{4^2} - \cdots,$$

which is convergent by comparison with the p series ($p > 1$).

The series in the above example has $[-1, 1]$ as the *interval of convergence*. This may be written $-1 \leq x \leq 1$, or indicated graphically as follows:



ILLUSTRATIVE EXAMPLE 2. Determine the interval of convergence for the series

$$1 + \frac{x^2}{2} + \frac{x^4}{4} + \cdots + \frac{x^{2n}}{2n} + \frac{x^{2n+2}}{2n+2} + \cdots.$$

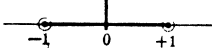
Solution. Omitting the first term, the test ratio is

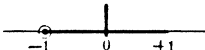
$$\frac{u_{n+1}}{u_n} = \frac{2n}{2n+2}x^2 = \frac{1}{(2n+1)(2n+2)}x^2.$$

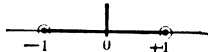
Also $\lim_{n \rightarrow \infty} \frac{1}{(2n+1)(2n+2)} = 0$. Hence the series converges for all values of x .

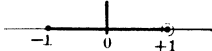
PROBLEMS

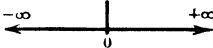
For what values of the variable are the following series convergent? *Graphical representations of intervals of convergence**

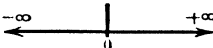
1. $1 + x + x^2 + x^3 + \dots$. Ans. $-1 < x < 1$. 

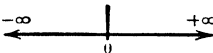
2. $x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots$. Ans. $-1 < x \leq 1$. 

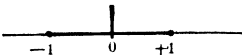
3. $x + x^4 + x^9 + x^{16} + \dots$. Ans. $-1 < x < 1$. 

4. $x + \frac{x^2}{\sqrt{2}} + \frac{x^3}{\sqrt{3}} + \dots$. Ans. $-1 \leq x < 1$. 

5. $1 + x + \frac{x^2}{2} + \frac{x^3}{3} + \dots$. Ans. All values of x . 

6. $1 - \frac{\theta^2}{2} + \frac{\theta^4}{4} - \frac{\theta^6}{6} + \dots$. Ans. All values of θ . 

7. $\phi - \frac{\phi^3}{3} + \frac{\phi^5}{5} - \frac{\phi^7}{7} + \dots$. Ans. All values of ϕ . 

8. $x + \frac{1}{2} \cdot \frac{x^3}{3} + \frac{1 \cdot 3}{2 \cdot 4} \cdot \frac{x^5}{5} + \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6} \cdot \frac{x^7}{7} + \dots$. 
Ans. $-1 \leq x \leq 1$.

9. $x + 2x^2 + 3x^3 + 4x^4 + \dots$. Ans. $-1 < x < 1$.

10. $1 - x + \frac{x^2}{2^2} - \frac{x^3}{3^2} + \dots$. $-1 \leq x \leq 1$.

11. $\frac{x}{1 \cdot 2} - \frac{x^2}{2 \cdot 2^2} + \frac{x^3}{3 \cdot 2^3} - \frac{x^4}{4 \cdot 2^4} + \dots$. $-2 < x \leq 2$.

12. $x + \frac{2x^2}{2} + \frac{3x^3}{3} + \frac{4x^4}{4} + \dots$. All values.

13. $1 + \frac{x^2}{2 \cdot 2^2} + \frac{1 \cdot 3 x^4}{2 \cdot 4 \cdot 2^4} + \frac{1 \cdot 3 \cdot 5 x^6}{2 \cdot 4 \cdot 6 \cdot 2^6} + \dots$. $-2 < x < 2$.

14. $\frac{ax}{2} + \frac{a^2 x^2}{5} + \frac{a^3 x^3}{10} + \dots + \frac{a^n x^n}{n^2 + 1} + \dots$. ($a > 0$) $-\frac{1}{a} \leq x \leq \frac{1}{a}$.

* End points that are not included in the interval of convergence have circles drawn about them.

$$15. 1 + \frac{x}{a} + \frac{x^2}{2a^2} + \frac{x^3}{3a^3} + \dots \quad (a > 0) \quad \text{Ans. } -a \leq x < a.$$

$$16. 1 + \frac{2^2 x}{[2]} + \frac{3^2 x^2}{[3]} + \frac{4^2 x^3}{[4]} + \dots \quad \text{All values.}$$

$$17. \frac{1}{3} + \frac{2x}{2 \cdot 3^2} + \frac{3x^2}{2^2 \cdot 3^3} + \frac{4x^3}{2^3 \cdot 3^4} + \dots \quad -6 < x < 6.$$

$$18. x + 4x^2 + 9x^3 + 16x^4 + \dots$$

$$19. \frac{x}{1 \cdot 2} + \frac{2x^2}{2 \cdot 2 \cdot 3} + \frac{3x^3}{2^2 \cdot 3 \cdot 4} + \frac{4x^4}{2^3 \cdot 4 \cdot 5} + \dots$$

$$20. \frac{1}{2} + \frac{x}{3} + \frac{x^2}{4} + \frac{x^3}{5} + \dots \quad 22. 1 - \frac{x}{10} + \frac{[2]x^2}{100} - \frac{[3]x^3}{1000} + \dots$$

$$21. \frac{10x}{1} + \frac{100x^2}{[2]} + \frac{1000x^3}{[3]} + \dots \quad 23. x + \frac{x^3}{3} + \frac{x^5}{5} + \frac{x^7}{7} + \dots$$

$$24. 1 - \frac{x^2}{2^2} + \frac{x^4}{4^2} - \frac{x^6}{6^2} + \dots$$

192. The binomial series. This important series is

$$(1) \quad 1 + mx + \frac{m(m-1)}{1 \cdot 2} x^2 + \frac{m(m-1)(m-2)}{1 \cdot 2 \cdot 3} x^3 + \dots \\ + \frac{m(m-1)(m-2) \cdots (m-n+1)}{[n]} x^n + \dots$$

where m is a constant.

If m is a positive integer, (1) is a finite series of $m+1$ terms, since all terms following that containing x^m have the factor $m-m$ in the numerator and vanish. In this case (1) is the result obtained by raising $1+x$ to the m th power. If m is not a positive integer, the series is an infinite series.

Now test (1) for convergence. We have

$$u_n = \frac{m(m-1)(m-2) \cdots (m-n+2)}{1 \cdot 2 \cdot 3 \cdots (n-1)} x^{n-1};$$

$$\text{and } u_{n+1} = \frac{m(m-1)(m-2) \cdots (m-n+2)(m-n+1)}{1 \cdot 2 \cdot 3 \cdots (n-1)n} x^n.$$

$$\text{Hence } \frac{u_{n+1}}{u_n} = \frac{m-n+1}{n} x = \left(\frac{m+1}{n} - 1 \right) x.$$

Then, since $\lim_{n \rightarrow \infty} \left(\frac{m+1}{n} - 1 \right) = -1$, we see that $\rho = -x$,

and the series is convergent if x is numerically less than 1, and divergent when x is numerically greater than 1.

Maclaurin's Series, Art. 194, implies the following statement.

Assuming that m is not a positive integer and that $|x| < 1$, the value of the binomial series is precisely the value of $(1+x)^m$. That is,

$$(2) \quad (1+x)^m = 1 + mx + \frac{m(m-1)}{1 \cdot 2} x^2 + \cdots \quad (|x| < 1)$$

If m is a positive integer, the series is finite and equals the value of the left-hand member for *all values* of x .

Equation (2) expresses the *special binomial theorem*. We may also write

$$(3) \quad (a+b)^m = a^m(1+x)^m, \text{ if } x = \frac{b}{a}.$$

Thus the left-hand member of (3) may also be expressed as a power series.

Examples of approximate computation by the binomial series are given below.

ILLUSTRATIVE EXAMPLE. Find $\sqrt[3]{630}$ approximately, using the binomial series.

Solution. The perfect square nearest to 630 is 625. Hence we write

$$\sqrt[3]{630} = \sqrt[3]{625 + 5} = 25(1 + \frac{1}{125})^{\frac{1}{3}}.$$

Now write out (2) with $m = \frac{1}{3}$. The result is

$$(1+x)^{\frac{1}{3}} = 1 + \frac{1}{3}x - \frac{1}{9}x^2 + \frac{1}{6}x^3 - \frac{5}{81}x^4 + \cdots$$

In this example, $x = \frac{1}{125} = 0.008$. Hence

$$(1 + \frac{1}{125})^{\frac{1}{3}} = 1 + 0.004 - 0.000008 + 0.00000032 + \cdots$$

(4) $25(1 + \frac{1}{125})^{\frac{1}{3}} = 25 + 0.1 - 0.0002 + 0.0000008 = 25.099801$ (to the nearest figure in the sixth decimal place). *Ans.*

The series in (4) is an alternating series, and the error in the answer is less than 0.0000008.

193. Another type of power series. We shall frequently use series of the form

$$(1) \quad b_0 + b_1(x-a) + b_2(x-a)^2 + \cdots + b_n(x-a)^n + \cdots$$

in which a and the coefficients $b_0, b_1, \cdots, b_n, \cdots$ are constants. Such a series is called a *power series in* $(x-a)$.

Let us apply the test-ratio test to (1), as in Art. 191. Then, if

$$\lim_{n \rightarrow \infty} \frac{b_{n+1}}{b_n} = M,$$

we shall have, for any fixed value of x ,

$$\rho = \lim_{n \rightarrow \infty} \frac{u_{n+1}}{u_n} = (x - a)M.$$

We have two cases:

- I. If $M = 0$, series (1) is convergent for all values of x .
- II. If M is not zero, series (1) will converge for the interval

$$a - \frac{1}{|M|} < x < a + \frac{1}{|M|}.$$

A convergent power series in x is adapted for computation when x is near zero. Series (1), if convergent, is useful when x is near the fixed value a , given in advance.

ILLUSTRATIVE EXAMPLE. Test the infinite series

$$1 - (x - 1) + \frac{(x - 1)^2}{2} - \frac{(x - 1)^3}{3} + \cdots$$

for convergence.

Solution. Neglecting the first term, we have

$$\frac{u_{n+1}}{u_n} = -\frac{n}{n+1}(x-1).$$

Also,
$$\lim_{n \rightarrow \infty} \left(\frac{n}{n+1} \right) = 1.$$

Hence $|\rho| = |x - 1|$, and the series will converge when x lies between 0 and 2. The end point $x = 2$ may be included.

PROBLEMS

1. Using the binomial series, show that

$$\frac{1}{1+x} = 1 - x + x^2 - x^3 + \cdots.$$

Verify the answer by direct division.

Using the binomial series, find approximately the values of the following numbers.

2. $\sqrt[3]{98}.$

5. $\sqrt[5]{35}.$

8. $\frac{1}{\sqrt[3]{990}}.$

11. $\sqrt{\frac{26}{25}}.$

3. $\sqrt[3]{120}.$

6. $\frac{1}{412}.$

9. $\frac{1}{\sqrt[4]{15}}.$

12. $\sqrt[3]{\frac{128}{125}}.$

4. $\sqrt[4]{630}.$

7. $\frac{1}{\sqrt[4]{412}}.$

10. $\frac{1}{\sqrt[5]{30}}.$

13. $\sqrt[4]{\frac{17}{16}}.$

For what values of the variable are the following series convergent?

14. $(x+1) - \frac{(x+1)^2}{2} + \frac{(x+1)^3}{3} - \frac{(x+1)^4}{4} + \dots$. *Ans.* $-2 < x \leq 0$.

15. $(x-1) + \frac{(x-1)^2}{\sqrt{2}} + \frac{(x-1)^3}{\sqrt{3}} + \frac{(x-1)^4}{\sqrt{4}} + \dots$. $0 \leq x < 2$.

16. $2(2x+1) + \frac{3(2x+1)^2}{|2|} + \frac{4(2x+1)^3}{|3|} + \dots$. All values.

17. $1 + (x-2) + \frac{(x-2)^2}{2^2} + \frac{(x-2)^3}{3^2} + \frac{(x-2)^4}{4^2} + \dots$.

18. $1 - 2(2x-3) + 3(2x-3)^2 - 4(2x-3)^3 + \dots$.

19. $\frac{x-3}{1 \cdot 3} + \frac{(x-3)^2}{2 \cdot 3^2} + \frac{(x-3)^3}{3 \cdot 3^3} + \frac{(x-3)^4}{4 \cdot 3^4} + \dots$.

CHAPTER XX

EXPANSION OF FUNCTIONS

194. Maclaurin's series. In this chapter the question of representing a function by a power series, or, otherwise expressed, developing (expanding) the function in a power series, will be discussed.

A convergent power series in x is obviously a function of x for all values in the interval of convergence. Thus we may write

$$(1) \quad f(x) = a_0 + a_1x + a_2x^2 + \cdots + a_nx^n + \cdots.$$

If, then, a function is represented by a power series, what must be the form of the coefficients a_0, a_1, \cdots, a_n , etc.? To answer this question we proceed thus:

Set $x = 0$ in (1). Then we must have

$$(2) \quad f(0) = a_0.$$

Hence the first coefficient a_0 in (1) is determined. Now *assume* that the series in (1) may be differentiated term by term, and that this differentiation may be continued. Then we shall have

$$(3) \quad \begin{cases} f'(x) = a_1 + 2 a_2x + 3 a_3x^2 + \cdots + na_nx^{n-1} + \cdots \\ f''(x) = 2 a_2 + 6 a_3x + \cdots + n(n-1)a_nx^{n-2} + \cdots \\ f'''(x) = 6 a_3 + \cdots + n(n-1)(n-2)a_nx^{n-3} + \cdots \end{cases}$$

etc.

Letting $x = 0$, the results are

$$(4) \quad f'(0) = a_1, \quad f''(0) = 2 a_2, \quad f'''(0) = 3 a_3, \cdots, \quad f^{(n)}(0) = n a_n.$$

Solving (4) for a_1, a_2, \cdots, a_n , etc., and substituting in (1), we obtain

$$(A) \quad f(x) = f(0) + f'(0) \frac{x}{1} + f''(0) \frac{x^2}{2} + \cdots + f^{(n)}(0) \frac{x^n}{n} + \cdots.$$

This formula expresses $f(x)$ as a power series. We say, "the function $f(x)$ is developed (or expanded) in a power series in x ." This is Maclaurin's series (or formula).*

* Named after Colin Maclaurin (1698-1746), and first published in his "Treatise of Fluxions" (Edinburgh, 1742). The series is really due to Stirling (1692-1770).

It is now necessary to examine (A) critically. For this purpose refer to (G), Art. 124, and rewrite it, letting $a = 0$, $b = x$. The result is

$$(5) \quad f(x) = f(0) + f'(0) \frac{x}{1} + f''(0) \frac{x^2}{2} + \cdots + f^{(n-1)}(0) \frac{x^{n-1}}{(n-1)} + R,$$

where
$$R = f^{(n)}(x_1) \frac{x^n}{n}. \quad (0 < x_1 < x)$$

The term R is called the *remainder after n terms*. The right-hand member of (5) agrees with Maclaurin's series (A) up to n terms. If we denote this sum by S_n , then (5) is

$$f(x) = S_n + R, \quad \text{or} \quad f(x) - S_n = R.$$

Now assume that, for a fixed value $x = x_0$, R approaches zero as a limit when n becomes infinite. Then S_n will approach $f(x_0)$ as a limit (Art. 14). That is, Maclaurin's series (A) will converge for $x = x_0$ and its value is $f(x_0)$. Thus we have the following result:

Theorem. *In order that the series (A) should converge and represent the function $f(x)$ it is necessary and sufficient that*

$$(6) \quad \lim_{n \rightarrow \infty} R = 0.$$

It is usually easier to determine the interval of convergence (as in the preceding chapter) than that for which (6) holds. But in simple cases the two are identical.

To represent a function $f(x)$ by the power series (A), it is obviously *necessary* that the function and its derivatives of all orders should be finite. This is, however, not *sufficient*.

Examples of functions that cannot be represented by a Maclaurin's series are

$$\ln x \quad \text{and} \quad \cot x,$$

since both become infinite when x is zero.

The student should not fail to note the importance of such an expansion as (A). In all practical computations results correct to a certain number of decimal places are sought, and since the process in question replaces a function perhaps difficult to calculate by an *ordinary polynomial with constant coefficients*, it is very useful in simplifying such computations. Of course we must use terms enough to give the desired degree of accuracy.

In the case of an alternating series (Art. 188) the error made by stopping at any term is numerically less than that term.

ILLUSTRATIVE EXAMPLE 1. Expand $\cos x$ into an infinite power series and determine for what values of x it converges.

Solution. Differentiating first and then placing $x = 0$, we get

$f(x) = \cos x,$	$f(0) = 1,$
$f'(x) = -\sin x,$	$f'(0) = 0,$
$f''(x) = -\cos x,$	$f''(0) = -1,$
$f'''(x) = \sin x,$	$f'''(0) = 0,$
$f^{iv}(x) = \cos x,$	$f^{iv}(0) = 1,$
$f^v(x) = -\sin x,$	$f^v(0) = 0,$
$f^{vi}(x) = -\cos x,$	$f^{vi}(0) = -1,$
etc.,	etc.

Substituting in (A),

$$(7) \quad \cos x = 1 - \frac{x^2}{2} + \frac{x^4}{4} - \frac{x^6}{6} + \cdots$$

Comparing with Problem 6, Art. 191, we see that the series converges for all values of x .

In the same way for $\sin x$,

$$(8) \quad \sin x = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \cdots,$$

which converges for all values of x (Problem 7, Art. 191).

In (7) and (8) it is not difficult to show that the remainder R approaches zero as a limit as n becomes infinite, when x has *any* fixed value. Consider (7). Here we may write the n th derivative in the form

$$f^{(n)}(x) = \cos\left(x + \frac{n\pi}{2}\right).$$

Hence
$$R = \cos\left(x_1 + \frac{n\pi}{2}\right) \frac{x^n}{n}.$$

Now $\cos\left(x_1 + \frac{n\pi}{2}\right)$ never exceeds 1 in numerical value. Also, the second factor of R is the n th term of the series

$$x + \frac{x^2}{2} + \frac{x^3}{3} + \cdots + \frac{x^n}{n} + \cdots,$$

which is convergent for all values of x . Therefore it approaches zero as n becomes infinite (see (A), Art. 185). Hence (6) holds.

From the above example we see that

$$\lim_{n \rightarrow \infty} \frac{x^n}{n} = 0.$$

Also, on the page preceding, we had

$$R = f^{(n)}(x_1) \frac{x^n}{n}. \quad (0 < x_1 < x)$$

Hence $\lim_{n \rightarrow \infty} R = 0$ if $f^{(n)}(x_1)$ remains finite when n becomes infinite.

ILLUSTRATIVE EXAMPLE 2. Using the series (8) found in the last example, calculate $\sin 1$ correct to four decimal places.

Solution. Here $x = 1$ radian; that is, the angle is expressed in circular measure. Therefore, substituting $x = 1$ in (8) of the last example,

$$\sin 1 = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} \cdots$$

Summing up the positive and negative terms separately,

$$\begin{array}{rcl} 1 & = & 1.00000 \cdots \\ \frac{1}{3} & = & 0.16667 \cdots \\ \frac{1}{5} & = & 0.00833 \cdots \\ \frac{1}{7} & = & 0.00020 \cdots \\ \hline & & 1.00833 \cdots \qquad \qquad \qquad 0.16687 \cdots \end{array}$$

$$\text{Hence} \qquad \sin 1 = 1.00833 - 0.16687 = 0.84146 \cdots,$$

which is correct to five decimal places, since the error made must be less than $\frac{1}{9}$; that is, less than 0.000003. Obviously the value of $\sin 1$ may be calculated to any desired degree of accuracy by simply including a sufficient number of additional terms.

PROBLEMS

Verify the following expansions of functions by Maclaurin's series and determine for what values of the variable they are convergent.

$$1. e^x = 1 + x + \frac{x^2}{2} + \frac{x^3}{3} + \cdots + \frac{x^{n-1}}{n-1} + \cdots. \qquad \text{Ans. All values.}$$

$$2. \sin x = x - \frac{x^3}{3} + \frac{x^5}{5} - \cdots + \frac{(-1)^n x^{2n-1}}{2n-1} + \cdots. \qquad \text{All values.}$$

$$3. \ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots + \frac{(-1)^n x^n}{n} + \cdots, \qquad -1 < x \leq 1.$$

$$4. \ln(1-x) = -x - \frac{x^2}{2} - \frac{x^3}{3} - \frac{x^4}{4} - \cdots - \frac{x^n}{n} - \cdots, \qquad -1 \leq x < 1.$$

$$\begin{aligned} 5. \arcsin x &= x + \frac{1 \cdot x^3}{2 \cdot 3} + \frac{1 \cdot 3 \cdot x^5}{2 \cdot 4 \cdot 5} + \cdots \\ &\quad + \frac{1 \cdot 3 \cdots (2n-3)x^{2n-1}}{2 \cdot 4 \cdots (2n-2)(2n-1)} + \cdots. \qquad -1 \leq x \leq 1. \end{aligned}$$

$$6. \arctan x = x - \frac{x^3}{3} + \frac{x^5}{5} - \cdots + \frac{(-1)^n x^{2n-1}}{2n-1} + \cdots. \qquad -1 \leq x \leq 1.$$

$$7. \sin\left(\frac{\pi}{4} + x\right) = \frac{1}{\sqrt{2}} \left(1 + x - \frac{x^2}{2} - \frac{x^3}{3} + \frac{x^4}{4} + \frac{x^5}{5} - \frac{x^6}{6} - \frac{x^7}{7} + \cdots\right).$$

Ans. All values.

$$\begin{aligned} 8. \ln(a+x) &= \ln a + \frac{x}{a} - \frac{x^2}{2a^2} + \frac{x^3}{3a^3} - \cdots \\ &\quad + \frac{(-1)^n x^{n-1}}{(n-1)a^{n-1}} + \cdots. \qquad -a < x \leq a. \end{aligned}$$

Verify the following expansions.

9. $\tan x = x + \frac{x^3}{3} + \frac{2x^5}{15} + \frac{17x^7}{315} + \dots$
10. $\sec x = 1 + \frac{x^2}{2} + \frac{5x^4}{24} + \frac{61x^6}{720} + \dots$
11. $\sin\left(\frac{\pi}{3} + x\right) = \frac{1}{2}\left(\sqrt{3} + x - \frac{\sqrt{3}x^2}{2} - \frac{x^3}{3} + \frac{\sqrt{3}x^4}{4} + \frac{x^5}{5} \dots\right)$
12. $\tan\left(\frac{\pi}{4} + x\right) = 1 + 2x + 2x^2 + \frac{8x^3}{3} + \dots$
13. $\arctan \frac{1}{x} = \frac{\pi}{2} - x + \frac{x^3}{3} - \frac{x^5}{5} + \dots$
14. $\frac{1}{2}(e^x + e^{-x}) = 1 + \frac{x^2}{2} + \frac{x^4}{4} + \frac{x^6}{6} + \dots$
15. $\ln(x + \sqrt{1+x^2}) = x - \frac{x^3}{3} + \frac{9x^5}{5} \dots$
16. $\ln \cos x = -\frac{x^2}{2} - \frac{x^4}{12} - \frac{x^6}{45} \dots$

Find three terms of the expansion in powers of x of each of the following functions.

17. $\cos\left(x - \frac{\pi}{4}\right)$
18. $\sin(x+1)$
19. $e^{\sin x}$
20. $\frac{1}{2}(e^x - e^{-x})$

Compute the values of the following functions by substituting directly in the equivalent power series, taking terms enough to make the results agree with those given below.

21. $e = 2.7182 \dots$

Solution. Let $x = 1$ in the series of Problem 1; then

$$e = 1 + 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5} + \dots$$

First term = 1.00000

Second term = 1.00000

Third term = 0.50000

Fourth term = 0.16667 ...

(Dividing third term by 3.)

Fifth term = 0.04167 ...

(Dividing fourth term by 4.)

Sixth term = 0.00833 ...

(Dividing fifth term by 5.)

Seventh term = 0.00139 ...

(Dividing sixth term by 6.)

Eighth term = 0.00020 ..., etc.

(Dividing seventh term by 7.)

Adding, $e = 2.71826 \dots$ Ans.

22. $\arctan\left(\frac{1}{5}\right) = 0.1973 \dots$; use series in Problem 6.

23. $\cos 1 = 0.5403 \dots$; use series in (7), Illustrative Example 1.

24. $\cos 10^\circ = 0.9848 \dots$; use series in (7), Illustrative Example 1.

25. $\sin 0.1 = 0.0998 \dots$; use series in Problem 2.

26. $\arcsin 1 = 1.5708 \dots$; use series in Problem 5.

27. $\sin \frac{\pi}{4} = 0.7071 \dots$; use series in Problem 2.

28. $\sin 0.5 = 0.4794 \dots$; use series in Problem 2.

29. $e^2 = 1 + 2 + \frac{2^2}{2!} + \frac{2^3}{3!} + \dots = 7.3890.$

30. $\sqrt{e} = 1 + \frac{1}{2} + \frac{1}{2^2 2!} + \frac{1}{2^3 3!} + \dots = 1.6487.$

195. Operations with infinite series. One can carry out many of the operations of algebra and the calculus with convergent series just as one can with polynomials. The following statements are given without proof.

Let
$$a_0 + a_1x + a_2x^2 + \dots + a_nx^n + \dots$$
and
$$b_0 + b_1x + b_2x^2 + \dots + b_nx^n + \dots$$

be convergent power series. Then we obtain new convergent power series from them as follows:

1. *By adding (or subtracting) term by term.*

$$(a_0 \pm b_0) + (a_1 \pm b_1)x + \dots + (a_n \pm b_n)x^n + \dots$$

2. *By multiplication and grouping terms.*

$$a_0b_0 + (a_0b_1 + a_1b_0)x + (a_0b_2 + a_1b_1 + a_2b_0)x^2 + \dots$$

ILLUSTRATIVE EXAMPLE 1. Computation of logarithms. From the series (Problems 3 and 4, Art. 194)

$$\ln(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 + \dots,$$

$$\ln(1-x) = -x - \frac{1}{2}x^2 - \frac{1}{3}x^3 - \frac{1}{4}x^4 - \dots,$$

we obtain, by subtraction of corresponding terms, and using (2), Art. 1, the new series

$$(1) \quad \ln \frac{1+x}{1-x} = 2\left(x + \frac{1}{3}x^3 + \frac{1}{5}x^5 + \frac{1}{7}x^7 + \dots\right).$$

This series converges when $|x| < 1$.

To transform (1) into a form better adapted to computation, let N be a positive number. Then, if we set

$$(2) \quad x = \frac{1}{2N+1}, \quad \text{whence} \quad \frac{1+x}{1-x} = \frac{N+1}{N},$$

then $|x| < 1$ for all values of N . Substituting in (1), we get the formula

$$(3) \quad \ln(N+1) = \ln N + 2 \left[\frac{1}{2N+1} + \frac{1}{3} \frac{1}{(2N+1)^3} + \frac{1}{5} \frac{1}{(2N+1)^5} + \dots \right].$$

This series converges for all positive values of N , and is well adapted to computation. For example, let $N = 1$. Then

$$\ln(N+1) = \ln 2, \quad \frac{1}{2N+1} = \frac{1}{3}.$$

Substituting in (3), the result is $\ln 2 = 0.69315$.

Placing $N = 2$ in (3), we get

$$\ln 3 = \ln 2 + 2 \left[\frac{1}{5} + \frac{1}{3} \cdot \frac{1}{5^3} + \frac{1}{5} \cdot \frac{1}{5^5} + \cdots \right] = 1.09861 \cdots.$$

It is only necessary to compute the logarithms of prime numbers in this way, the logarithms of composite numbers being then found by using formulas (2), Art. 1. Thus,

$$\ln 8 = \ln 2^3 = 3 \ln 2 = 2.07944 \cdots,$$

$$\ln 6 = \ln 3 + \ln 2 = 1.79176 \cdots.$$

All the above are *Napierian*, or *natural*, *logarithms*, that is, the base is $e = 2.71828 \cdots$. If we wish to find *Briggs's*, or *common*, *logarithms*, where the base 10 is employed, all we need to do is to change the base by means of the formula

$$\log n = \frac{\ln n}{\ln 10}.$$

Thus,
$$\log 2 = \frac{\ln 2}{\ln 10} = \frac{0.69315}{2.30258} = 0.3010 \cdots.$$

In the actual computation of a table of logarithms only a few of the tabulated values are calculated from series, all the rest being found by employing theorems in the theory of logarithms and various ingenious devices designed for the purpose of saving work.

ILLUSTRATIVE EXAMPLE 2. Find the power series for $e^x \sin x$.

Solution. From the series

$$\sin x = x - \frac{x^3}{6} + \frac{x^5}{120} - \cdots \quad \text{Problem 2, Art. 194}$$

and
$$e^x = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + \frac{x^4}{24} + \frac{x^5}{120} \quad \text{Problem 1, Art. 194}$$

we obtain, by multiplication,

$$e^x \sin x = x + x^2 + \frac{x^3}{3} - \frac{x^5}{30} + \text{terms in } x^6 \text{ etc.} \quad \text{Ans.}$$

3. By division. A special case is shown in the example below.

ILLUSTRATIVE EXAMPLE 3. Find the series for $\sec x$ from the series for $\cos x$ (see (7), Art. 194).

$$(4) \quad \cos x = 1 - \frac{x^2}{2} + \frac{x^4}{24} - \frac{x^6}{720} + \cdots.$$

Solution. From the formula $\sec x = \frac{1}{\cos x}$, we see that we have to carry through the division of 1 by the series (4). This is best done as follows.

Write (4) in the form $\cos x = 1 - z$, where

$$(5) \quad z = \frac{x^2}{2} - \frac{x^4}{24} + \frac{x^6}{720} - \cdots.$$

Then

$$(6) \quad \sec x = \frac{1}{1-z} = 1 + z + z^2 + z^3 + \cdots,$$

if $|z| < 1$ (Problem 1, Art. 193).

From (5), we have the series

$$z^2 = \frac{x^4}{4} - \frac{x^6}{24} + \text{terms of higher degree,}$$

$$z^3 = \frac{x^6}{8} + \dots$$

Substituting in (6), the result is

$$\sec x = 1 + \frac{1}{2}x^2 + \frac{5}{24}x^4 + \frac{61}{720}x^6 + \dots \quad \text{Ans.}$$

PROBLEMS

Given $\ln 2 = 0.69315$, $\ln 3 = 1.09861$, calculate the following natural logarithms by the method of the example above.

1. $\ln 5 = 1.60944$.

3. $\ln 11 = 2.39790$.

2. $\ln 7 = 1.94591$.

4. $\ln 13 = 2.56495$.

Work out the following series.

5. $e^{-t} \cos t = 1 - t + \frac{1}{2}t^2 - \frac{1}{6}t^3 + \dots$

6. $\frac{e^x}{1-x} = 1 + 2x + \frac{5}{2}x^2 + \frac{8}{3}x^3 + \frac{65}{24}x^4 + \dots$

7. $\frac{\cos x}{\sqrt{1+x}} = 1 - \frac{1}{2}x - \frac{1}{8}x^2 - \frac{1}{16}x^3 + \frac{49}{384}x^4 + \dots$

8. $\frac{\sin \frac{1}{2}\theta}{1 - \frac{1}{2}\theta} = \frac{1}{2}\theta + \frac{1}{4}\theta^2 + \frac{5}{48}\theta^3 + \frac{5}{96}\theta^4 + \dots$

9. $\frac{\sqrt{1-x^2}}{\cos x} = 1 - \frac{1}{6}x^4 + \dots$

10. $e^x \tan x = x + x^2 + \frac{5}{6}x^3 + \frac{1}{2}x^4 + \dots$

11. $e^{-x} \sec x = 1 - x + x^2 - \frac{2}{3}x^3 + \frac{1}{2}x^4 + \dots$

12. $e^{-\frac{t}{2}} \sin 2t = 2t - t^2 - \frac{13}{12}t^3 + \frac{5}{8}t^4 + \dots$

13. $(1+x) \cos \sqrt{x} = 1 + \frac{1}{2}x - \frac{11}{24}x^2 + \frac{29}{720}x^3 - \frac{11}{8064}x^4 + \dots$

14. $(1+2x) \operatorname{arcsin} x = x + 2x^2 + \frac{1}{6}x^3 + \frac{1}{3}x^4 + \dots$

15. $\sqrt{1-x} \operatorname{arctan} x = x - \frac{1}{2}x^2 - \frac{11}{24}x^3 + \frac{5}{48}x^4 + \dots$

16. $\sqrt{1-\tan x} = 1 - \frac{1}{2}x - \frac{1}{8}x^2 - \frac{11}{48}x^3 - \frac{47}{384}x^4 + \dots$

$$17. \sqrt{\sec x} = 1 + \frac{1}{4}x^2 + \frac{7}{96}x^4 + \dots$$

$$18. \frac{\ln(1+x)}{1+\sin x} = x - \frac{3}{2}x^2 + \frac{11}{6}x^3 - \frac{23}{12}x^4 + \dots$$

$$19. \frac{1}{\sqrt{5-e^x}} = \frac{1}{2} + \frac{1}{16}x + \frac{11}{256}x^2 + \frac{151}{6144}x^3 + \dots$$

$$20. \sqrt{4+\sin \phi} = 2 + \frac{1}{4}\phi - \frac{1}{64}\phi^2 - \frac{61}{1536}\phi^3 + \dots$$

For the following functions find all terms of the series which involve powers of x less than x^5 .

$$21. e^{-\frac{x}{5}} \sin x.$$

$$24. \sqrt{3+e^{-x}}.$$

$$22. e^x \cos \frac{1}{2}\sqrt{x}.$$

$$25. \frac{\ln(1+x)}{\sqrt{1+x}},$$

$$23. \frac{\sin x}{\cos 2x}.$$

$$26. \sqrt{5-\cos x}.$$

196. Differentiation and integration of power series. A convergent power series

$$(1) \quad a_0 + a_1x + a_2x^2 + a_3x^3 + \dots + a_nx^n + \dots$$

may be differentiated term by term for any value of x within the interval of convergence, and the resulting series is also convergent.

For example, from the series

$$\sin x = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \dots$$

we obtain, by differentiation, the new series

$$\cos x = 1 - \frac{x^2}{2} + \frac{x^4}{4} - \frac{x^6}{6} + \dots$$

Both series converge for all values of x (see Problems 6 and 7, Art. 191).

Again, the series (1) may be integrated term by term if the limits lie within the interval of convergence, and the resulting series will converge.

ILLUSTRATIVE EXAMPLE 1. Find the series for $\ln(1+x)$ by integration.

Solution. Since $\frac{d}{dx} \ln(1+x) = \frac{1}{1+x}$, we have

$$(2) \quad \ln(1+x) = \int_0^x \frac{dx}{1+x}.$$

$$\text{Now} \quad \frac{1}{1+x} = 1 - x + x^2 - x^3 + x^4 - \dots,$$

when $|x| < 1$ (Art. 192). Substituting in (2) and integrating the right-hand member term by term, we obtain the result

$$\ln(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 + \cdots.$$

This series also converges when $|x| < 1$ (see Problem 2, Art. 191).

ILLUSTRATIVE EXAMPLE 2. Find the power series for $\arcsin x$ by integration.

Solution. Since $\frac{d}{dx} \arcsin x = \frac{1}{\sqrt{1-x^2}}$, we have

$$(3) \quad \arcsin x = \int_0^x \frac{dx}{\sqrt{1-x^2}}. \quad (x^2 < 1)$$

By the binomial series ((2), Art. 192), letting $m = -\frac{1}{2}$, and replacing x by $-x^2$, we have

$$\frac{1}{\sqrt{1-x^2}} = 1 + \frac{1}{2}x^2 + \frac{1 \cdot 3}{2 \cdot 4}x^4 + \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6}x^6 + \cdots.$$

This series converges when $|x| < 1$. Substituting in (3) and integrating term by term, we get

$$\arcsin x = x + \frac{1}{2} \cdot \frac{x^3}{3} + \frac{1 \cdot 3}{2 \cdot 4} \cdot \frac{x^5}{5} + \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6} \cdot \frac{x^7}{7} + \cdots. \text{ Ans.}$$

This series converges also when $|x| < 1$ (see Problem 8, Art. 191).

By this series, the value of π is readily computed. For, since the series converges for values of x between -1 and $+1$, we may let $x = \frac{1}{2}$, giving

$$\frac{\pi}{6} = \frac{1}{2} + \frac{1}{2} \cdot \frac{1}{3} \left(\frac{1}{2}\right)^3 + \frac{1 \cdot 3}{2 \cdot 4} \cdot \frac{1}{5} \left(\frac{1}{2}\right)^5 + \cdots,$$

or

$$\pi = 3.1415 \cdots.$$

Evidently we might have used the series of Problem 6, Art. 194, instead. Both of these series converge rather slowly, but there are other series, found by more elaborate methods, by means of which the correct value of π to a large number of decimal places may easily be calculated.

ILLUSTRATIVE EXAMPLE 3. Using series, find approximately the value of $\int_0^1 \sin x^2 dx$.

Solution. Let $z = x^2$. Then

$$\sin z = z - \frac{z^3}{3} + \frac{z^5}{5} - \cdots, \quad \text{Problem 2, Art. 194}$$

$$\text{Hence} \quad \sin x^2 = x^2 - \frac{x^6}{3} + \frac{x^{10}}{5} - \cdots,$$

$$\text{and} \quad \int_0^1 \sin x^2 dx = \int_0^1 \left(x^2 - \frac{x^6}{3} + \frac{x^{10}}{5} \right) dx, \text{ approximately,}$$

$$\begin{aligned} &= \left[\frac{x^3}{3} - \frac{x^7}{42} + \frac{x^{11}}{1320} \right]_0^1 = 0.3333 - 0.0238 + 0.0008 \\ &= 0.3103. \text{ Ans.} \end{aligned}$$

PROBLEMS

1. Find the series for arc tan x by integration.
2. Find the series for $\ln(1-x)$ by integration.
3. Find the series for $\sec^2 x$ by differentiating the series for $\tan x$.
4. Find the series for $\ln \cos x$ by integrating the series for $\tan x$.

Using series, find approximately the values of the following integrals.

5. $\int_0^{\frac{1}{2}} \frac{\cos x \, dx}{1+x}$. *Ans.* 0.3914. 9. $\int_0^{\frac{1}{2}} \frac{\ln(1+x) \, dx}{\cos x}$. *Ans.* 0.0295.
6. $\int_0^{\frac{1}{2}} \frac{\sin x \, dx}{1-x}$. 0.185. 10. $\int_0^1 e^{-x^2} \, dx$.
7. $\int_0^{\frac{1}{2}} e^x \ln(1+x) \, dx$. 0.0628. 11. $\int_0^{\frac{1}{2}} \ln(1+\sqrt{x}) \, dx$.
8. $\int_0^{\frac{1}{2}} \frac{e^{-x^2} \, dx}{\sqrt{1-x^2}}$. 0.4815. 12. $\int_0^1 e^x \sin \sqrt{x} \, dx$.
13. $\int_0^1 \sqrt{4-x^3} \, dx$. 14. $\int_0^1 e^{-x^2} \cos \sqrt{x} \, dx$. 15. $\int_0^1 \sqrt{2-\sin x} \, dx$.

197. Approximate formulas derived from Maclaurin's series. By using a few terms of the power series by which a function is represented, we obtain for the function an approximate formula which possesses some degree of accuracy. Such approximate formulas are widely used in applied mathematics.

For example, taking the binomial series ((2), Art. 192), we may write down at once the following approximate formulas.

<i>First approximation</i>	<i>Second approximation</i>
$(1+x)^m = 1 + mx$	$(1+x)^m = 1 + mx + \frac{1}{2} m(m-1)x^2;$
$\frac{1}{(1+x)^m} = 1 - mx$	$\frac{1}{(1+x)^m} = 1 - mx + \frac{1}{2} m(m-1)x^2.$

In these $|x|$ is small and m is positive.

Again, consider the sine series

$$(1) \qquad \sin x = x - \frac{x^3}{3} + \frac{x^5}{5} - \dots$$

Then

$$(2) \qquad \sin x = x,$$

$$(3) \qquad \sin x = x - \frac{x^3}{6},$$

etc.

are approximate formulas. Let us examine the first.

In the series in (1), assume values of x such that the terms decrease. If the first term only is retained, the value of the remaining series is numerically less than its first term $\frac{1}{6}x^3$ (Art. 188). That is,

$$\sin x = x, \text{ with } |\text{error}| < \left| \frac{1}{6}x^3 \right|.$$

We may inquire, For what range of values of x will (2) hold to three decimal places? Then

$$\left| \frac{1}{6}x^3 \right| < 0.0005,$$

that is,

$$|x| < \sqrt[3]{0.003} < 0.1443 \text{ rad.}$$

We then conclude that formula (2) is correct to three decimal places for values of x between -0.1443 and $+0.1443$, or, in degrees, for values between $-8^\circ.2$ and $+8^\circ.2$.

PROBLEMS

1. How accurate is the approximate formula $\sin x = x - \frac{x^3}{6}$ when (a) $x = 30^\circ$? (b) $x = 60^\circ$? (c) $x = 90^\circ$?

Ans. (a) Error < 0.00033 ; (b) error < 0.01 ; (c) error < 0.08 .

2. How accurate is the approximate formula $\cos x = 1 - \frac{x^2}{2}$ when (a) $x = 30^\circ$? (b) $x = 60^\circ$? (c) $x = 90^\circ$?

Ans. (a) Error < 0.0032 ; (b) error < 0.05 ; (c) error < 0.25 .

3. How accurate is the approximate formula $e^{-x} = 1 - x$ when (a) $x = 0.1$? (b) $x = 0.5$?

4. How accurate is the approximate formula $\arctan x = x - \frac{x^3}{3}$ when (a) $x = 0.1$? (b) $x = 0.5$? (c) $x = 1$?

Ans. (a) Error < 0.000002 ; (b) error < 0.006 ; (c) error < 0.2 .

5. How many terms of the series $\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \dots$ must be taken to give $\sin 45^\circ$ correct to five decimals? *Ans.* Four.

6. How many terms of the series $\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \dots$ must be taken to give $\cos 60^\circ$ correct to five decimals?

7. How many terms of the series $\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots$ must be taken to give $\log 1.2$ correct to five decimals? *Ans.* Six.

Verify the following approximate formulas:

$$8. \frac{\sin x}{1-x} = x + x^2.$$

$$12. \int e^{-x^2} dx = C + x - \frac{x^3}{3} + \frac{x^5}{10}.$$

$$9. \frac{\cos x}{1-x^2} = 1 + \frac{x^2}{2}.$$

$$13. \int \ln(1-x) dx = C - \frac{x^2}{2} - \frac{x^3}{6}.$$

$$10. e^{-\theta} \cos \theta = 1 - \theta + \frac{\theta^3}{3}.$$

$$14. \int \arcsin x dx = C + \frac{x^2}{2} + \frac{x^4}{24}.$$

$$11. \int \cos \sqrt{x} dx = C + x - \frac{x^2}{4} + \frac{x^3}{12}.$$

$$15. \int e^\theta \sin \theta d\theta = C + \frac{\theta^2}{2} + \frac{\theta^3}{3}.$$

198. Taylor's series. A convergent power series in x is well adapted for calculating the value of the function which it represents for *small* values of x (near zero). We now derive an expansion in powers of $x - a$ (see Art. 193), where a is a fixed number. The series thus obtained is adapted for calculation of the function represented by it for values of x near a .

Assume that

$$(1) f(x) = b_0 + b_1(x - a) + b_2(x - a)^2 + \cdots + b_n(x - a)^n + \cdots,$$

and that the series represents the function. The *necessary* form of the coefficients b_0, b_1 , etc. is obtained as in Art. 194. That is, we differentiate (1) with respect to x , assuming that this is possible, and continue the process. Thus we have

$$\begin{aligned} f'(x) &= b_1 + 2b_2(x - a) + \cdots + nb_n(x - a)^{n-1} + \cdots, \\ f''(x) &= 2b_2 + \cdots + n(n-1)b_n(x - a)^{n-2} + \cdots, \end{aligned}$$

etc.

Substituting $x = a$ in these equations and in (1), and solving for b_0, b_1, b_2, \dots , we obtain

$$b_0 = f(a), \quad b_1 = f'(a), \quad b_2 = \frac{f''(a)}{2}, \quad \dots, \quad b_n = \frac{f^{(n)}(a)}{n}, \quad \dots$$

Replacing these values in (1), the result is

$$\begin{aligned} (B) \quad f(x) &= f(a) + f'(a) \frac{(x - a)}{1} + f''(a) \frac{(x - a)^2}{2} + \cdots \\ &\quad + f^{(n)}(a) \frac{(x - a)^n}{n} + \cdots. \end{aligned}$$

The series is called *Taylor's series* (or *formula*).*

Let us now examine (B) critically. Referring to (G), Art. 124, and letting $b = x$, the result may be written thus:

$$(2) f(x) = f(a) + f'(a) \frac{(x - a)}{1} + \cdots + f^{(n-1)}(a) \frac{(x - a)^{n-1}}{n-1} + R,$$

where

$$R = f^{(n)}(x_1) \frac{(x - a)^n}{n}. \quad (a < x_1 < x)$$

The term R is called the *remainder after n terms*.

Now the series in the right-hand member of (2) agrees with Taylor's series (B) up to n terms. Denote the sum of these terms by S_n . Then, from (2), we have

$$f(x) = S_n + R, \quad \text{or} \quad f(x) - S_n = R.$$

* Published by Dr. Brook Taylor (1685-1731) in his "Methodus Incrementorum" (London, 1715).

Now assume that, for a fixed value $x = x_0$, the remainder R approaches zero as a limit when n becomes infinite. Then

$$(3) \quad \lim_{n \rightarrow \infty} S_n = f(x_0),$$

and (B) converges for $x = x_0$ and its value is $f(x_0)$.

Theorem. *The infinite series (B) represents the function for those values of x , and those only, for which the remainder approaches zero as the number of terms increases without limit.*

If the series converges for values of x for which the remainder does not approach zero as n increases without limit, then for such values of x the series does not represent the function $f(x)$.

It is usually easier to determine the interval of convergence of the series than that for which the remainder approaches zero; but in simple cases the two intervals are identical.

When the values of a function and its successive derivatives are known and finite for some fixed value of the variable, as $x = a$, then (B) is used for finding the value of the function for values of x near a , and (B) is also called *the expansion of $f(x)$ in the neighborhood of $x = a$.*

ILLUSTRATIVE EXAMPLE 1. Expand $\ln x$ in powers of $(x - 1)$.

Solution.

$$f(x) = \ln x, \quad f(1) = 0,$$

$$f'(x) = \frac{1}{x}, \quad f'(1) = 1,$$

$$f''(x) = -\frac{1}{x^2}, \quad f''(1) = -1,$$

$$f'''(x) = \frac{2}{x^3}, \quad f'''(1) = 2,$$

$$\text{etc.,} \quad \text{etc.}$$

Substituting in (B), $\ln x = x - 1 - \frac{1}{2}(x - 1)^2 + \frac{1}{3}(x - 1)^3 - \dots$. *Ans.*

This converges for values of x between 0 and 2 and is the *expansion of $\ln x$ in the vicinity of $x = 1$.* See Illustrative Example, Art. 193.

ILLUSTRATIVE EXAMPLE 2. Expand $\cos x$ in powers of $\left(x - \frac{\pi}{4}\right)$ to four terms.

Solution. Here $f(x) = \cos x$ and $a = \frac{\pi}{4}$. Then we have

$$f(x) = \cos x, \quad f\left(\frac{\pi}{4}\right) = \frac{1}{\sqrt{2}},$$

$$f'(x) = -\sin x, \quad f'\left(\frac{\pi}{4}\right) = -\frac{1}{\sqrt{2}},$$

$$f''(x) = -\cos x, \quad f''\left(\frac{\pi}{4}\right) = -\frac{1}{\sqrt{2}},$$

$$f'''(x) = \sin x, \quad f'''\left(\frac{\pi}{4}\right) = \frac{1}{\sqrt{2}},$$

$$\text{etc.,} \quad \text{etc.}$$

The series is, therefore,

$$\cos x = \frac{1}{\sqrt{2}} - \frac{1}{\sqrt{2}} \left(x - \frac{\pi}{4}\right) - \frac{1}{\sqrt{2}} \frac{\left(x - \frac{\pi}{4}\right)^2}{[2]} + \frac{1}{\sqrt{2}} \frac{\left(x - \frac{\pi}{4}\right)^3}{[3]} + \dots$$

The result may be written in the form

$$\cos x = 0.70711 \left[1 - \left(x - \frac{\pi}{4}\right) - \frac{1}{2} \left(x - \frac{\pi}{4}\right)^2 + \frac{1}{6} \left(x - \frac{\pi}{4}\right)^3 \dots \right].$$

To check this result let us calculate $\cos 50^\circ$. Then $x - \frac{\pi}{4} = 5^\circ$ expressed in radians, or $x - \frac{\pi}{4} = 0.08727$, $\left(x - \frac{\pi}{4}\right)^2 = 0.00762$, $\left(x - \frac{\pi}{4}\right)^3 = 0.00066$. With these values the series above gives $\cos 50^\circ = 0.64278$. Five-place tables give $\cos 50^\circ = 0.64279$.

199. Another form of Taylor's series. In (B), Art. 198, if we replace a by x_0 and let $x - a = h$, that is, $x = a + h = x_0 + h$, the result is

$$(C) f(x_0 + h) = f(x_0) + f'(x_0) \frac{h}{[1]} + f''(x_0) \frac{h^2}{[2]} + \dots + f^{(n)}(x_0) \frac{h^n}{[n]} + \dots$$

In this second form the *new value* of $f(x)$ when x changes from x_0 to $x_0 + h$ is expanded in a power series in h , the increment of x .

ILLUSTRATIVE EXAMPLE. Expand $\sin x$ in a power series in h when x changes from x_0 to $x_0 + h$.

Solution. Here $f(x) = \sin x$, and $f(x_0 + h) = \sin(x_0 + h)$. Differentiate and arrange the work as below.

$$\begin{array}{ll} f(x) = \sin x, & f(x_0) = \sin x_0, \\ f'(x) = \cos x, & f'(x_0) = \cos x_0, \\ f''(x) = -\sin x, & f''(x_0) = -\sin x_0, \\ \text{etc.}, & \text{etc.} \end{array}$$

Substituting in (C), we obtain

$$\sin(x_0 + h) = \sin x_0 + \cos x_0 \frac{h}{[1]} - \sin x_0 \frac{h^2}{[2]} - \cos x_0 \frac{h^3}{[6]} + \dots \quad \text{Ans.}$$

PROBLEMS

Verify the following series by Taylor's formula.

$$1. e^x = e^a \left[1 + (x - a) + \frac{(x - a)^2}{[2]} + \frac{(x - a)^3}{[3]} + \dots \right].$$

$$2. \sin x = \sin a + (x - a) \cos a - \frac{(x - a)^2}{[2]} \sin a - \frac{(x - a)^3}{[3]} \cos a + \dots$$

$$3. \cos x = \cos a - (x - a) \sin a - \frac{(x - a)^2}{[2]} \cos a + \frac{(x - a)^3}{[3]} \sin a + \dots$$

$$4. \ln(a + x) = \ln a + \frac{x}{a} - \frac{x^2}{2a^2} + \frac{x^3}{3a^3} + \dots$$

$$5. \cos(a+x) = \cos a - x \sin a - \frac{x^2}{2} \cos a + \frac{x^3}{3} \sin a + \dots$$

$$6. \tan(x+h) = \tan x + h \sec^2 x + h^2 \sec^2 x \tan x + \dots$$

$$7. (x+h)^n = x^n + nx^{n-1}h + \frac{n(n-1)}{2} x^{n-2}h^2 + \frac{n(n-1)(n-2)}{3} x^{n-3}h^3 + \dots$$

8. Expand $\sin x$ in powers of $\left(x - \frac{\pi}{4}\right)$ to four terms.

$$\text{Ans. } \sin x = \frac{1}{\sqrt{2}} \left[1 + \left(x - \frac{\pi}{4}\right) - \frac{\left(x - \frac{\pi}{4}\right)^2}{2} - \frac{\left(x - \frac{\pi}{4}\right)^3}{3} + \dots \right]$$

9. Expand $\tan x$ in powers of $\left(x - \frac{\pi}{4}\right)$ to three terms.

$$\text{Ans. } \tan x = 1 + 2\left(x - \frac{\pi}{4}\right) + 2\left(x - \frac{\pi}{4}\right)^2 + \dots$$

10. Expand $\ln x$ in powers of $(x-2)$ to four terms.

11. Expand e^x in powers of $(x-1)$ to five terms.

12. Expand $\sin\left(\frac{\pi}{6} + x\right)$ in powers of x to four terms.

13. Expand $\cot\left(\frac{\pi}{4} + x\right)$ in powers of x to three terms.

200. Approximate formulas derived from Taylor's series. Such formulas are provided by using some terms of series (B) or (C).

For example, if $f(x) = \sin x$, we have (see Problem 2, Art. 199)

$$(1) \quad \sin x = \sin a + \cos a(x-a)$$

as a first approximation.

A second approximation results by taking three terms of the series. This is

$$(2) \quad \sin x = \sin a + \cos a(x-a) - \sin a \frac{(x-a)^2}{2}$$

From (1), transposing $\sin a$ and dividing by $x-a$, we get

$$(3) \quad \frac{\sin x - \sin a}{x-a} = \cos a.$$

Since $\cos a$ is constant, this means that (approximately)

The change in the value of the sine is proportional to the change in the angle for values of the angle near a .

Formula (3) illustrates *interpolation by proportional parts*.

ILLUSTRATIVE EXAMPLE 1. For example, let $a = 30^\circ = 0.5236$ radian, and suppose it is required to calculate the sines of 31° and 32° by the approximate formula (1). Then, since $x - a = 1^\circ = 0.01745$ radian,

$$\begin{aligned}\sin 31^\circ &= \sin 30^\circ + \cos 30^\circ (0.01745) \\ &= 0.5000 + 0.8660 \times 0.01745 \\ &= 0.5000 + 0.0151 = 0.5151.\end{aligned}$$

Similarly,

$$\sin 32^\circ = \sin 30^\circ + \cos 30^\circ (0.03490) = 0.5302.$$

These values by (1) are correct to three decimal places only. If greater accuracy is desired, we may use (2).

$$\begin{aligned}\text{Then} \quad \sin 31^\circ &= \sin 30^\circ + \cos 30^\circ (0.01745) - \frac{\sin 30^\circ}{2} (0.01745)^2 \\ &= 0.50000 + 0.01511 - 0.00008 \\ &= 0.51503.\end{aligned}$$

$$\begin{aligned}\sin 32^\circ &= \sin 30^\circ + \cos 30^\circ (0.03490) - \frac{\sin 30^\circ}{2} (0.03490)^2 \\ &= 0.50000 + 0.03022 - 0.00030 \\ &= 0.52992.\end{aligned}$$

These results are correct to four decimal places.

From (C) we derive approximate formulas for the increment of $f(x)$ when x changes from x_0 to $x_0 + h$. For, transposing the first term of the right-hand member, we get

$$(4) \quad f(x_0 + h) - f(x_0) = f'(x_0)h + f''(x_0) \frac{h^2}{2} + \dots$$

The left-hand member expresses the increment of $f(x)$ as a power series in the increment of x ($= h$).

From (4) we derive, as a *first approximation*,

$$(5) \quad f(x_0 + h) - f(x_0) = f'(x_0)h.$$

This formula was used in Art. 92. For the left-hand member is the value of the differential of $f(x)$ for $x = x_0$ and $\Delta x = h$.

As a *second approximation*, we have

$$(6) \quad f(x_0 + h) - f(x_0) = f'(x_0)h + f''(x_0) \frac{h^2}{2}.$$

ILLUSTRATIVE EXAMPLE 2. Calculate the increment of $\tan x$, approximately, when x changes from 45° to 46° , by (5) and by (6).

Solution. From Problem 6, Art. 199, if $x = x_0$, we have

$$\tan(x_0 + h) = \tan x_0 + \sec^2 x_0 h + \sec^2 x_0 \tan x_0 h^2 + \dots$$

In this example $x_0 = 45^\circ$, and $\tan x_0 = 1$, $\sec^2 x_0 = 2$.

Also, $h = 1^\circ$ expressed in radians $= 0.01745$. Hence, by (5),

$$\tan 46^\circ - \tan 45^\circ = 2(0.01745) = 0.0349;$$

by (6), $\tan 46^\circ - \tan 45^\circ = 0.0349 + 2(0.01745)^2 = 0.0349 + 0.0006 = 0.0355$.

From the second approximation we get $\tan 46^\circ = 1.0355$, which is correct to four places of decimals.

PROBLEMS

1. Verify the approximate formula

$$\ln(10 + x) = 2.303 + \frac{x}{10}.$$

Calculate the value of the function from this formula and compare your result with the tables, when (a) $x = -0.5$; (b) $x = -1$.

Ans. (a) Formula, 2.253; tables, 2.251.

(b) Formula, 2.203; tables, 2.197.

2. Verify the approximate formula

$$\sin\left(\frac{\pi}{6} + x\right) = 0.5 + 0.8660 x.$$

Use the formula to calculate $\sin 27^\circ$, $\sin 33^\circ$, $\sin 40^\circ$, and compare your results with the tables.

3. Verify the approximate formula

$$\tan\left(\frac{\pi}{4} + x\right) = 1 + 2x + 2x^2.$$

Use the formula to calculate $\tan 46^\circ$, $\tan 50^\circ$, and compare your results with the tables.

4. Verify the approximate formula

$$\cos x = \cos a - (x - a) \sin a.$$

Given

$$\cos 30^\circ = \sin 60^\circ = 0.8660,$$

$$\cos 45^\circ = \sin 45^\circ = 0.7071,$$

and

$$\cos 60^\circ = \sin 30^\circ = 0.5,$$

use the formula to calculate $\cos 32^\circ$, $\cos 47^\circ$, $\cos 62^\circ$, and compare your results with the tables.

ADDITIONAL PROBLEMS

1. Given the definite integral
- $\int_0^{\frac{1}{2}} x^5 \ln(1+x) dx$
- .

(a) Obtain its value by series correct to four decimal places. *Ans.* 0.0009.

(b) Obtain its value by direct computation and compare with the approximate value derived in (a).

(c) Prove that if n terms of the series are used in the computation the error is less than $\frac{1}{2^{n+7}(n+1)(n+7)}.$

2. Given
- $f(x) = e^{-\frac{x}{2}} \cos \frac{x}{2}.$

(a) Show that $f^{(4)}(x) = -\frac{1}{4} f(x).$

(b) Expand $f(x)$ in a Maclaurin series to six terms.

(c) What is the coefficient of x^{12} in this series?

$$\text{Ans. } -\frac{1}{64 \cdot 12}.$$

CHAPTER XXI

ORDINARY DIFFERENTIAL EQUATIONS *

201. Differential equations — order and degree. A differential equation is an equation involving derivatives or differentials. Differential equations have been frequently employed in this book. The illustrative examples of Art. 139 afford simple examples. Thus, from the differential equation (Illustrative Example 1)

$$(1) \quad \frac{dy}{dx} = 2x,$$

we found, by integrating,

$$(2) \quad y = x^2 + C.$$

Again (Illustrative Example 2), integration of the differential equation

$$(3) \quad \frac{dy}{dx} = -\frac{x}{y}$$

led to the solution

$$(4) \quad x^2 + y^2 = 2C.$$

Equations (1) and (3) are examples of ordinary differential equations of the *first order*, and (2) and (4) are, respectively, the **complete solutions**.

Another example is

$$(5) \quad \frac{d^2y}{dx^2} + y = 0.$$

This is a differential equation of the *second order*, so named from the order of the derivative.

The *order of a differential equation* is the same as that of the derivative of highest order appearing in it.

The derivative of highest order appearing in a differential equation may be affected with exponents. The largest exponent gives the *degree* of the differential equation.

Thus, the differential equation

$$(6) \quad y''^2 = (1 + y'^2)^3,$$

* A few types only of differential equations are treated in this chapter, namely, such types as the student is likely to encounter in elementary work in mechanics and physics.

where y' and y'' are, respectively, the first and second derivatives of y with respect to x , is of the second degree and second order.

202. Solutions of differential equations. Constants of integration. A *solution* or *integral* of a differential equation is a relation between the variables involved by which the equation is satisfied. Thus

$$(1) \quad y = a \sin x$$

is a solution of the differential equation

$$(2) \quad \frac{d^2y}{dx^2} + y = 0.$$

For, differentiating (1),

$$(3) \quad \frac{d^2y}{dx^2} = -a \sin x.$$

Now, if we substitute from (1) and (3) in (2), we get

$$-a \sin x + a \sin x = 0,$$

and (2) is satisfied. Here a is an arbitrary constant. In the same manner

$$(4) \quad y = b \cos x$$

may be shown to be a solution of (2) for any value of b . The relation

$$(5) \quad y = c_1 \sin x + c_2 \cos x$$

is a still more general solution of (2). In fact, by giving particular values to c_1 and c_2 it is seen that the solution (5) includes the solutions (1) and (4).

The arbitrary constants c_1 and c_2 appearing in (5) are called *constants of integration*. A solution such as (5), which contains a number of arbitrary essential constants equal to the order of the equation (in this case two), is called the *complete* or *general solution*.* Solutions obtained therefrom by giving particular values to the constants are called *particular solutions*. In practice, a particular solution is obtained from the complete solution by given conditions to be satisfied by the particular solution.

ILLUSTRATIVE EXAMPLE. The complete solution of the differential equation

$$(1) \quad y'' + y = 0$$

is $y = c_1 \cos x + c_2 \sin x$ (see (5) above).

Find a particular solution such that

$$(2) \quad y = 2, \quad y' = -1, \quad \text{when } x = 0.$$

* It is shown in works on differential equations that the general solution has n arbitrary constants when the differential equation is of the n th order.

Solution. From the complete solution

$$(3) \quad y = c_1 \cos x + c_2 \sin x,$$

by differentiation, we obtain

$$(4) \quad y' = -c_1 \sin x + c_2 \cos x.$$

Substituting in (3) and (4) from (2), we find $c_1 = 2$, $c_2 = -1$. Putting these values in (3) gives the particular solution required, $y = 2 \cos x - \sin x$. *Ans.*

The solution of a differential equation is considered as having been effected when it has been reduced to an expression involving integrals, whether the actual integration can be effected or not.

203. Verification of the solutions of differential equations. Before taking up the problem of solving differential equations, we show how to verify a given solution.

ILLUSTRATIVE EXAMPLE 1. Show that

$$(1) \quad y = c_1 x \cos \ln x + c_2 x \sin \ln x + x \ln x$$

is a solution of the differential equation

$$(2) \quad x^2 \frac{d^2 y}{dx^2} - x \frac{dy}{dx} + 2y = x \ln x.$$

Solution. Differentiating (1), we get

$$(3) \quad \frac{dy}{dx} = (c_2 - c_1) \sin \ln x + (c_2 + c_1) \cos \ln x + \ln x + 1,$$

$$(4) \quad \frac{d^2 y}{dx^2} = -(c_2 + c_1) \frac{\sin \ln x}{x} + (c_2 - c_1) \frac{\cos \ln x}{x} + \frac{1}{x}.$$

Substituting from (1), (3), (4), in (2), we find that the equation is identically satisfied.

ILLUSTRATIVE EXAMPLE 2. Show that

$$(5) \quad y^2 - 4x = 0$$

is a particular solution of the differential equation

$$(6) \quad xy'^2 - 1 = 0.$$

Solution. Differentiating (5), the result is

$$yy' - 2 = 0, \quad \text{whence} \quad y' = \frac{2}{y}.$$

Substituting this value of y' in (6) and reducing, we obtain $4x - y^2 = 0$, which is true by (5).

PROBLEMS

Verify the following solutions of the corresponding differential equations.

*Differential equations**Solutions*

1. $\frac{d^2y}{dx^2} - \frac{1}{x} \frac{dy}{dx} + \frac{2}{x} = 0.$ $y = c_1 + 2x + c_2x^2.$
2. $\frac{d^2V}{dr^2} + \frac{2}{r} \frac{dV}{dr} = 0.$ $V = \frac{c_1}{r} + c_2.$
3. $\frac{d^2s}{dt^2} - \frac{ds}{dt} - 6s = 0.$ $s = c_1e^{-2t} + c_2e^{3t}.$
4. $\frac{d^3x}{dt^3} + 2\frac{d^2x}{dt^2} - \frac{dx}{dt} - 2x = 0.$ $x = c_1e^t + c_2e^{-t} + c_3e^{-2t}.$
5. $\left(\frac{dy}{dx}\right)^3 - 4xy \frac{dy}{dx} + 8y^2 = 0.$ $y = c(x - c)^2.$
6. $x \frac{d^2y}{dx^2} + 2 \frac{dy}{dx} - xy = 0.$ $xy = 2e^x - 3e^{-x}.$
7. $\frac{d^2s}{dt^2} + 4s = 0.$ $s = c_1 \cos(2t + c_2).$
8. $\frac{d^2x}{dt^2} - 6 \frac{dx}{dt} + 13x = 39.$ $x = e^{3t} \cos 2t + 3.$
9. $y \frac{d^2y}{dx^2} - \left(\frac{dy}{dx}\right)^2 + \frac{dy}{dx} = 0.$ $y = ae^{\frac{x}{b}} - b.$
10. $xy \frac{d^2y}{dx^2} + x \left(\frac{dy}{dx}\right)^2 - y \frac{dy}{dx} = 0.$ $\frac{x^2}{c_1} + \frac{y^2}{c_2} = 1.$
11. $\frac{du}{dv} = \frac{1+u^2}{1+v^2}.$ $u = \frac{c+v}{1-cv}.$
12. $\frac{d^2s}{dt^2} + 4s = 8t.$ $s = 2 \sin 2t + \cos 2t + 2t.$
13. $\frac{d^2y}{dx^2} - 2 \frac{dy}{dx} - 3y = e^{2x}.$ $y = c_1e^{3x} + c_2e^{-x} - \frac{1}{3}e^{2x}.$
14. $\frac{d^2x}{dt^2} + 9x = 5 \cos 2t.$ $x = \cos 2t + 2 \cos 3t + 3 \sin 3t.$
15. $\frac{d^2x}{dt^2} + 9x = 3 \cos 3t.$ $x = c_1 \cos 3t + c_2 \sin 3t + \frac{1}{2}t \sin 3t.$
16. $\frac{dy}{dx} + xy = x^3y^3.$ $\frac{1}{y^2} = x^2 + 1 + ce^{x^2}.$

204. Differential equations of the first order and of the first degree.
Such an equation may be brought into the form

$$(A) \quad M dx + N dy = 0,$$

in which M and N are functions of x and y . The more common differential equations coming under this head may be divided into four types.

Type I. Variables separable. When the terms of a differential equation can be so arranged that it takes on the form

$$(1) \quad f(x)dx + F(y)dy = 0,$$

where $f(x)$ is a function of x alone and $F(y)$ is a function of y alone, the process is called *separation of the variables*, and the solution is obtained by direct integration. Thus, integrating (1), we get the general solution

$$(2) \quad \int f(x)dx + \int F(y)dy = c,$$

where c is an arbitrary constant.

Equations which are not given in the simple form (1) may often be brought into that form by means of the following rule for separating the variables.

FIRST STEP. *Clear of fractions; and if the equation involves derivatives, multiply through by the differential of the independent variable.*

SECOND STEP. *Collect all the terms containing the same differential into a single term. If the equation then takes on the form*

$$XY dx + X'Y'dy = 0,$$

where X, X' are functions of x alone, and Y, Y' are functions of y alone, it may be brought to the form (1) by dividing through by $X'Y$.

THIRD STEP. *Integrate each part separately, as in (2).*

ILLUSTRATIVE EXAMPLE 1. Solve the equation

$$\frac{dy}{dx} = \frac{1 + y^2}{(1 + x^2)xy}.$$

Solution. *First Step.* $(1 + x^2)xy dy = (1 + y^2)dx$.

Second Step. $(1 + y^2)dx - x(1 + x^2)y dy = 0$.

To separate the variables we now divide by $x(1 + x^2)(1 + y^2)$, giving

$$\frac{dx}{x(1 + x^2)} - \frac{y dy}{1 + y^2} = 0.$$

Third Step. $\int \frac{dx}{x(1 + x^2)} - \int \frac{y dy}{1 + y^2} = C,$

$$\int \frac{dx}{x} - \int \frac{x dx}{1 + x^2} - \int \frac{y dy}{1 + y^2} = C,$$

Art. 167

$$\ln x - \frac{1}{2} \ln (1 + x^2) - \frac{1}{2} \ln (1 + y^2) = C,$$

$$\ln (1 + x^2)(1 + y^2) = 2 \ln x - 2 C.$$

This result may be written in more compact form if we replace $-2C$ by $\ln c$, that is, give a new form to the arbitrary constant. Our solution then becomes

$$\begin{aligned}\ln(1+x^2)(1+y^2) &= \ln x^2 + \ln c, \\ \ln(1+x^2)(1+y^2) &= \ln cx^2, \\ (1+x^2)(1+y^2) &= cx^2. \quad \text{Ans.}\end{aligned}$$

ILLUSTRATIVE EXAMPLE 2. Solve the equation

$$a\left(x \frac{dy}{dx} + 2y\right) = xy \frac{dy}{dx}.$$

Solution. *First Step.*

$$ax \, dy + 2ay \, dx = xy \, dy.$$

Second Step.

$$2ay \, dx + x(a-y) \, dy = 0.$$

To separate the variables we divide by xy .

$$\frac{2a \, dx}{x} + \frac{(a-y) \, dy}{y} = 0.$$

Third Step.

$$2a \int \frac{dx}{x} + a \int \frac{dy}{y} - \int dy = C,$$

$$2a \ln x + a \ln y - y = C,$$

$$a \ln x^2 y = C + y,$$

$$\ln x^2 y = \frac{C}{a} + \frac{y}{a}.$$

By passing from logarithms to exponentials this result may be written in the form

$$x^2 y = e^{\frac{C}{a} + \frac{y}{a}},$$

or

$$x^2 y = e^{\frac{C}{a}} \cdot e^{\frac{y}{a}}.$$

Denoting the constant $e^{\frac{C}{a}}$ by c , we get our solution in the form

$$x^2 y = ce^{\frac{y}{a}}. \quad \text{Ans.}$$

Type II. Homogeneous equations. The differential equation

$$(A) \quad M \, dx + N \, dy = 0$$

is said to be homogeneous when M and N are homogeneous functions of x and y of the same degree.* Such differential equations may be solved by making the substitution

$$(3) \quad y = vx.$$

This will give a differential equation in v and x in which the variables are separable, and hence we may follow the rule under Type I.

* A function of x and y is said to be *homogeneous* in the variables if the result of replacing x and y by λx and λy (λ being arbitrary) reduces to the original function multiplied by some power of λ . This power of λ is called the *degree* of the original function.

In fact, from (A) we obtain

$$(4) \quad \frac{dy}{dx} = -\frac{M}{N}.$$

Also, from (3),

$$(5) \quad \frac{dy}{dx} = x \frac{dv}{dx} + v.$$

The right-hand member of (4) will become a function of v only when the substitution (3) is used. Hence, by using (5) and (3), we shall obtain from (4)

$$(6) \quad x \frac{dv}{dx} + v = f(v),$$

and the variables x and v may be separated.

ILLUSTRATIVE EXAMPLE. Solve the equation

$$y^2 + x^2 \frac{dy}{dx} = xy \frac{dy}{dx}.$$

Solution. $y^2 dx + (x^2 - xy)dy = 0$.

Here $M = y^2$, $N = x^2 - xy$, and both are homogeneous and of the second degree in x and y . Also we have

$$\frac{dy}{dx} = \frac{y^2}{xy - x^2}.$$

Substitute $y = vx$. The result is

$$x \frac{dv}{dx} + v = -\frac{v^2}{1-v},$$

or

$$v dx + x(1-v)dv = 0.$$

To separate the variables, divide by vx . This gives

$$\frac{dx}{x} + \frac{(1-v)dv}{v} = 0,$$

$$\int \frac{dx}{x} + \int \frac{dv}{v} - \int dv = C,$$

$$\ln x + \ln v - v = C,$$

$$\ln vx = C + v,$$

$$vx = e^{C+v} = e^C \cdot e^v,$$

$$vx = ce^v.$$

But $v = \frac{y}{x}$. Hence the complete solution is

$$y = ce^{\frac{y}{x}}. \text{ Ans.}$$

PROBLEMS

Find the complete solution of each of the following differential equations.

1. $(2+y)dx - (3-x)dy = 0.$ *Ans.* $(2+y)(3-x) = c.$

2. $xy dx - (1+x^2)dy = 0.$ $cy^2 = 1+x^2.$

3. $x(x+3)dy - y(2x+3)dx = 0.$ $y = cx(x+3).$

4. $\sqrt{1+x^2} dy - \sqrt{1-y^2} dx = 0$. *Ans.* $\arcsin y = \ln c(x + \sqrt{1+x^2})$.

5. $d\rho + \rho \tan \theta d\theta = 0$. $\rho = c \cos \theta$.

6. $(1-x)dy - y^2 dx = 0$. $y \ln c(1-x) = 1$.

7. $(x+2y)dx + (2x-3y)dy = 0$. $x^2 + 4xy - 3y^2 = c$.

8. $(3x+5y)dx + (4x+6y)dy = 0$. $(x+y)^2(x+2y) = c$.

9. $2(x+y)dx + y dy = 0$.

Ans. $\frac{1}{2} \ln(2x^2 + 2xy + y^2) - \arctan\left(\frac{x+y}{x}\right) = c$.

10. $(8y+10x)dx + (5y+7x)dy = 0$. $(x+y)^2(2x+y)^3 = c$.

11. $(2x+y)dx + (x+3y)dy = 0$. $2x^2 + 2xy + 3y^2 = c$.

12. $\sqrt{1-4t^2} ds + 2\sqrt{1-s^2} dt = 0$. $s\sqrt{1-4t^2} + 2t\sqrt{1-s^2} = c$.

13. $2z(3z+1)dw + (1-2w)dz = 0$. $(2w-1)(1+3z) = 3cz$.

14. $2xdz - 2zdx = \sqrt{x^2+4z^2} dx$. $1+4cz - c^2x^2 = 0$.

15. $(x+4y)dx + 2xdy = 0$. $x^4 + 6x^2y = c$.

16. $(2x^2+y^2)dx + (2xy+3y^2)dy = 0$. $2x^4 + 3xy^2 + 3y^3 = c$.

17. $\frac{du}{dv} = \frac{1+u^2}{1+v^2}$. $u = \frac{v+c}{1-cv}$.

18. $(3+2y)x dx + (x^2-2)dy = 0$. 22. $(3x+y)dx + (x+y)dy = 0$.

19. $2(1+y)dx - (1-x)dy = 0$. 23. $xy(y+2)dx - (y+1)dy = 0$.

20. $(1+y)x dx - (1+x)y dy = 0$. 24. $(1+x^2)dy - (1-y^2)dx = 0$.

21. $(ax+b)dy - y^2 dx = 0$. 25. $(x-2y)dx - (2x+y)dy = 0$.

26. $(3x+2y)dx + x dy = 0$.

27. $3(5x+3y)dx + (11x+5y)dy = 0$.

28. $(x^2+y^2)dx + (2xy+y^2)dy = 0$.

29. $2y dx - (2x-y)dy = 0$.

In each of the following problems find the particular solution which is determined by the given values of x and y .

30. $\frac{dx}{y} + \frac{4dy}{x} = 0$; $x=4$, $y=2$. *Ans.* $x^2 + 4y^2 = 32$.

31. $(x^2+y^2)dx = 2xy dy$; $x=1$, $y=0$. $y^2 = x^2 - x$.

32. $x dy - y dx = \sqrt{x^2+y^2} dx$; $x=\frac{1}{2}$, $y=0$. $1+4y-4x^2=0$.

33. $(1+y^2)dy = y dx$; $x=2$, $y=2$.

34. Find the equation of the curve whose slope at any point is equal to $-\left(1+\frac{y}{x}\right)$ and which passes through the point $(2, 1)$. *Ans.* $x^2 + 2xy = 8$.

35. Find the equation of the curve whose slope at any point is equal to $\frac{y-1}{x^2+x}$ and which passes through the point $(1, 0)$. *Ans.* $y(1+x) = 1-x$.

Type III. Linear equations. The linear differential equation of the first order in y is of the form

$$(B) \quad \frac{dy}{dx} + Py = Q, \quad -$$

where P and Q are functions of x alone, or constants.

Similarly, the equation

$$(C) \quad \frac{dx}{dy} + Hx = J,$$

where H and J are functions of y or constants, is a linear differential equation.

To integrate (B), let

$$(7) \quad y = uz,$$

where z and u are functions of x to be determined. Differentiating (7),

$$(8) \quad \frac{dy}{dx} = u \frac{dz}{dx} + z \frac{du}{dx}.$$

Substituting from (8) and (7) in (B), the result is

$$(9) \quad u \frac{dz}{dx} + z \frac{du}{dx} + Puz = Q, \text{ or}$$

$$(9) \quad u \frac{dz}{dx} + \left(\frac{du}{dx} + Pu \right) z = Q.$$

We now determine u by integrating

$$(10) \quad \frac{du}{dx} + Pu = 0,$$

in which the variables x and u are separable. Using the value of u thus obtained, we find z by solving

$$(11) \quad u \frac{dz}{dx} = Q,$$

in which x and z can be separated. Obviously, the values of u and z thus found will satisfy (9), and the solution of (B) is then given by (7).

The following examples show the details.

ILLUSTRATIVE EXAMPLE 1. Solve the equation

$$(12) \quad \frac{dy}{dx} - \frac{2y}{x+1} = (x+1)^{\frac{1}{2}}.$$

Solution. This is evidently in the linear form (B), where

$$P = -\frac{2}{x+1} \quad \text{and} \quad Q = (x+1)^{\frac{1}{2}}.$$

Let $y = uz$; then

$$\frac{dy}{dx} = u \frac{dz}{dx} + z \frac{du}{dx}.$$

Substituting in the given equation (12), we get

$$u \frac{dz}{dx} + z \frac{du}{dx} - \frac{2uz}{1+x} = (x+1)^{\frac{5}{2}}, \text{ or}$$

$$(13) \quad u \frac{dz}{dx} + \left(\frac{du}{dx} - \frac{2u}{1+x} \right) z = (x+1)^{\frac{5}{2}}.$$

To determine u we place the coefficient of z equal to zero. This gives

$$\frac{du}{dx} - \frac{2u}{1+x} = 0,$$

$$\frac{du}{u} = \frac{2dx}{1+x}.$$

Integrating, we get $\ln u = 2 \ln (1+x) = \ln (1+x)^2$.

$$(14) \quad \therefore u = (1+x)^2. *$$

Equation (13) now becomes, since the term in z drops out,

$$u \frac{dz}{dx} = (x+1)^{\frac{5}{2}}.$$

Replacing u by its value from (14),

$$\frac{dz}{dx} = (x+1)^{\frac{1}{2}}.$$

Integrating, we get $dz = (x+1)^{\frac{1}{2}} dx$.

$$(15) \quad z = \frac{2(x+1)^{\frac{3}{2}}}{3} + C.$$

Substituting from (15) and (14) in $y = uz$, we get the complete solution

$$y = \frac{2(x+1)^{\frac{3}{2}}}{3} + C(x+1)^2. \text{ Ans.}$$

ILLUSTRATIVE EXAMPLE 2. Derive a formula for the complete solution of (B).

Solution. Solving (10), we have

$$\ln u + \int P dx = \ln k,$$

where $\ln k$ is the constant of integration;

$$\text{whence} \quad u = ke^{\int P dx}.$$

Substituting this value of u in (11), and separating the variables z and x , the result is

$$dz = \frac{Q}{k} e^{\int P dx} dx.$$

Integrating, and substituting in (7), we obtain

$$y = e^{\int P dx} \left(\int Q e^{\int P dx} dx + C \right). \text{ Ans.}$$

It should be observed that the constant k cancels out of the final result. For this reason it is customary to omit the constant of integration in solving (10).

* For the sake of simplicity we have assumed the particular value zero for the constant of integration. Otherwise we should have $u = c(1+x)^2$. But in the work that follows c finally cancels out (See Illustrative Example 2.)

Type IV. Equations reducible to the linear form. Some equations that are not linear can be reduced to the linear form by means of a suitable transformation. One type of such equations is

$$(D) \quad \frac{dy}{dx} + Py = Qy^n,$$

where P and Q are functions of x alone or constants. Equation (D) may be reduced to the linear form (B), Type III, by means of the substitution $z = y^{-n+1}$. Such a reduction, however, is not necessary if we employ the same method for finding the solution as that given under Type III. Let us illustrate this by means of an example.

ILLUSTRATIVE EXAMPLE. Solve the equation

$$(16) \quad \frac{dy}{dx} + \frac{y}{x} = a \ln x \cdot y^2.$$

Solution. This is evidently in the form (D), where

$$P = \frac{1}{x}, \quad Q = a \ln x, \quad n = 2.$$

Let $y = uz$; then $\frac{dy}{dx} = u \frac{dz}{dx} + z \frac{du}{dx}$.

Substituting in (16), we get

$$(17) \quad \begin{aligned} u \frac{dz}{dx} + z \frac{du}{dx} + \frac{uz}{x} &= a \ln x \cdot u^2 z^2, \\ u \frac{dz}{dx} + \left(\frac{du}{dx} + \frac{u}{x} \right) z &= a \ln x \cdot u^2 z^2. \end{aligned}$$

To determine u we place the coefficient of z equal to zero. This gives

$$\begin{aligned} \frac{du}{dx} + \frac{u}{x} &= 0, \\ \frac{du}{u} &= -\frac{dx}{x}. \end{aligned}$$

Integrating, we get $\ln u = -\ln x = \ln \frac{1}{x}$,

$$(18) \quad u = \frac{1}{x}.$$

Since the term in z drops out, equation (17) now becomes

$$\begin{aligned} u \frac{dz}{dx} &= a \ln x \cdot u^2 z^2, \\ \frac{dz}{dx} &= a \ln x \cdot uz^2. \end{aligned}$$

Replacing u by its value from (18),

$$\begin{aligned} \frac{dz}{dx} &= a \ln x \cdot \frac{z^2}{x}, \\ \frac{dz}{z^2} &= a \ln x \cdot \frac{dx}{x}. \end{aligned}$$

Integrating, we get $-\frac{1}{z} = \frac{a(\ln x)^2}{2} + C,$

$$(19) \quad z = -\frac{2}{a(\ln x)^2 + 2C}.$$

Substituting from (19) and (18) in $y = uz$, we get the complete solution

$$y = -\frac{1}{x} \cdot \frac{2}{a(\ln x)^2 + 2C},$$

or

$$xy[a(\ln x)^2 + 2C] + 2 = 0. \text{ Ans.}$$

PROBLEMS

Find the complete solution of each of the following differential equations.

$$1. \quad x \frac{dy}{dx} - 2y = 2x. \quad \text{Ans. } y = cx^2 - 2x.$$

$$2. \quad x \frac{dy}{dx} - 2y = -x. \quad y = x + cx^2.$$

$$3. \quad \frac{dy}{dx} - 2y = 1 - 2x. \quad y = x + ce^{2x}.$$

$$4. \quad x \frac{dy}{dx} - 3y = -2nx. \quad y = nx + cx^4.$$

$$5. \quad \frac{dy}{dx} - y = -2e^{-x}. \quad y = e^{-x} + ce^x.$$

$$6. \quad \frac{ds}{dt} - s \operatorname{ctn} t = 1 - (t+2) \operatorname{ctn} t. \quad s = t + 2 + c \sin t.$$

$$7. \quad \frac{dy}{dx} + \frac{2y}{x} = 2y^2. \quad cx^2y + 2xy - 1 = 0.$$

$$8. \quad \frac{ds}{dt} + s \tan t = 2t + t^2 \tan t. \quad s = t^2 + c \cos t.$$

$$9. \quad x \frac{dy}{dx} - y = (x-1)e^x. \quad y = e^x + cx.$$

$$10. \quad \frac{dy}{dx} + \frac{y}{x} = y^3. \quad cx^2y^2 + 2xy^2 - 1 = 0.$$

$$11. \quad \frac{ds}{dt} + \frac{s}{t} = \cos t + \frac{\sin t}{t}. \quad s = \sin t + \frac{c}{t}.$$

$$12. \quad nx \frac{dy}{dx} + 2y = xy^{n+1}. \quad cx^2y^n + xy^n - 1 = 0.$$

$$13. \quad \frac{ds}{dt} + s = \cos t - \sin t. \quad s = \cos t + ce^{-t}.$$

$$14. \quad \frac{ds}{dt} - s \operatorname{ctn} t = e^t(1 - \operatorname{ctn} t). \quad s = e^t + c \sin t.$$

15. $x \frac{dy}{dx} - 2y + 3x = 0.$

20. $\frac{ds}{dt} - s \operatorname{ctn} t + \operatorname{csc} t = 0.$

16. $\frac{dy}{dx} + y = 2 + 2x.$

21. $2 \frac{dy}{dx} + y = (x-1)y^3.$

17. $x \frac{dy}{dx} + y = (1+x)e^x.$

22. $x \frac{dy}{dx} - y = x \cos x - \sin x.$

18. $\frac{dy}{dx} - y = 1 - 2x.$

23. $n \frac{dy}{dx} - y + (x^2 + 2x)y^{n+1} = 0$

19. $x \frac{dy}{dx} + y + x^2y^2 = 0.$

24. $\frac{ds}{dt} + s \tan t = e^{-t}(\tan t - 1).$

In each of the following problems find the particular solution which is determined by the given values of x and y .

25. $\frac{dy}{dx} - \frac{2y}{x} = x^2e^x; x=1, y=0.$

Ans. $y = x^2(e^x - e).$

26. $\frac{dy}{dx} + \frac{2y}{x} = \frac{1}{x^2}; x=1, y=2.$

$y = \frac{x+1}{x^2}.$

27. $\frac{dy}{dx} + y \tan x = \sec x; x=0, y=-1.$

$y = \sin x - \cos x.$

28. $\frac{dy}{dx} - \frac{2y}{x+1} = (x+1)^3; x=0, y=1.$

$2y = (x+1)^4 + (x+1)^2.$

29. Find the equation of the curve whose slope at any point is equal to $\frac{2y+x+1}{x}$ and which passes through the point $(1, 0)$.

Ans. $2y = 3x^2 - 2x - 1.$

30. Find the equation of the curve whose slope at any point is equal to $\frac{y^2 \ln x - y}{x}$ and which passes through the point $(1, 1)$. *Ans.* $y(1 + \ln x) = 1.$

205. Two special types of differential equations of higher order. The differential equations discussed in this article occur frequently.

$$(E) \quad \frac{d^n y}{dx^n} = X,$$

where X is a function of x alone or a constant.

To integrate, first multiply both members by dx . Then, integrating, we have

$$\frac{d^{n-1}y}{dx^{n-1}} = \int \frac{d^n y}{dx^n} dx = \int X dx + c_1.$$

Repeat the process $(n-1)$ times. Then the complete solution containing n arbitrary constants will be obtained.

ILLUSTRATIVE EXAMPLE. Solve $\frac{d^3y}{dx^3} = xe^x$.

Solution. Multiplying both members by dx and integrating,

$$\frac{d^2y}{dx^2} = \int xe^x dx + C_1,$$

or
$$\frac{d^2y}{dx^2} = xe^x - e^x + C_1.$$

Repeating the process,

$$\frac{dy}{dx} = \int xe^x dx - \int e^x dx + \int C_1 dx + C_2,$$

or
$$\frac{dy}{dx} = xe^x - 2e^x + C_1x + C_2.$$

$$\begin{aligned} y &= \int xe^x dx - \int 2e^x dx + \int C_1x dx + \int C_2 dx + C_3 \\ &= xe^x - 3e^x + \frac{C_1x^2}{2} + C_2x + C_3. \end{aligned}$$

Hence $y = xe^x - 3e^x + c_1x^2 + c_2x + c_3$. Ans.

A second type of much importance is

$$(F) \quad \frac{d^2y}{dx^2} = Y,$$

where Y is a function of y alone.

To integrate, proceed thus. Write the equation

$$dy' = Y dx,$$

and multiply both members by y' . The result is

$$y' dy' = Y y' dx.$$

But $y' dx = dy$, and the preceding equation becomes

$$y' dy' = Y dy.$$

The variables y and y' are now separated. Integrating, the result is

$$\frac{1}{2} y'^2 = \int Y dy + C_1.$$

The right-hand member is a function of y . Extract the square root, separate the variables, x and y , and integrate again. The following example illustrates the method.

ILLUSTRATIVE EXAMPLE. Solve $\frac{d^2y}{dx^2} + a^2y = 0$.

Solution. Here $\frac{dy'}{dx} = \frac{d^2y}{dx^2} = -a^2y$, and hence the equation belongs to type (F).

Multiplying both members by $y' dx$ and proceeding as above, we get

$$y' dy' = -a^2y dy.$$

Integrating,

$$\frac{1}{2} y'^2 = -\frac{1}{2} a^2 y^2 + C.$$

$$y' = \sqrt{2C - a^2y^2}.$$

$$\frac{dy}{dx} = \sqrt{C_1 - a^2y^2},$$

setting $2C = C_1$ and taking the positive sign of the radical. Separating the variables, we get

$$\frac{dy}{\sqrt{C_1 - a^2 y^2}} = dx.$$

Integrating, $\frac{1}{a} \arcsin \frac{ay}{\sqrt{C_1}} = x + C_2,$

or $\arcsin \frac{ay}{\sqrt{C_1}} = ax + aC_2.$

This is the same as $\frac{ay}{\sqrt{C_1}} = \sin(ax + aC_2)$
 $= \sin ax \cos aC_2 + \cos ax \sin aC_2, \quad (4), \text{ Art. 2}$

or $y = \frac{\sqrt{C_1}}{a} \cos aC_2 \cdot \sin ax + \frac{\sqrt{C_1}}{a} \sin aC_2 \cdot \cos ax.$

Hence $y = c_1 \sin ax + c_2 \cos ax. \quad \text{Ans.}$

PROBLEMS

Find the complete solution of each of the following differential equations.

1. $\frac{d^2x}{dt^2} = t^2. \quad \text{Ans. } x = \frac{t^4}{12} + c_1t + c_2.$

2. $\frac{d^2x}{dt^2} = x. \quad x = c_1e^t + c_2e^{-t}.$

3. $\frac{d^2x}{dt^2} = 4 \sin 2t. \quad x = -\sin 2t + c_1t + c_2.$

4. $\frac{d^2x}{dt^2} = e^{2t}. \quad x = \frac{e^{2t}}{4} + c_1t + c_2.$

5. $\frac{d^2s}{dt^2} = \frac{1}{(s+1)^3}. \quad c_1(s+1)^2 = (c_1t + c_2)^2 + 1.$

6. $\frac{d^2s}{dt^2} = \frac{1}{\sqrt{as}}. \quad 3t = 2a^{\frac{1}{4}}(s^{\frac{1}{2}} - 2c_1)(s^{\frac{1}{2}} + c_1)^{\frac{1}{2}} + c_2.$

7. $\frac{d^2y}{dt^2} = \frac{a}{y^3}. \quad c_1y^2 = a + (c_1t + c_2)^2.$

8. $\frac{d^2y}{dx^2} + \frac{a^2}{y^2} = 0. \quad \text{Ans. } \sqrt{c_1y^2 + y} - \frac{1}{\sqrt{c_1}} \ln(\sqrt{c_1y} + \sqrt{1 + c_1y}) = ac_1\sqrt{2}x + c_2.$

9. $\frac{d^2s}{dt^2} + \frac{k}{s^2} = 0. \quad \text{Find } t, \text{ having given that } s = a, \frac{ds}{dt} = 0, \text{ when } t = 0.$

$\text{Ans. } t = \sqrt{\frac{a}{2k}} \left\{ \sqrt{as - s^2} + a \arcsin \sqrt{\frac{a-s}{a}} \right\}.$

10. $\frac{d^3y}{dx^3} = x + \sin x.$

11. $\frac{d^2s}{dt^2} = a \cos nt.$

12. $\frac{d^2y}{dx^2} = 4y.$

206. Linear differential equations of the second order with constant coefficients. Equations of the form

$$(G) \quad \frac{d^2y}{dx^2} + p \frac{dy}{dx} + qy = 0,$$

where p and q are constants, are important in applied mathematics.

To obtain a particular solution of (G), let us try to determine the value of the constant r so that (G) will be satisfied by

$$(1) \quad y = e^{rx}.$$

Differentiating (1), we obtain

$$(2) \quad \frac{dy}{dx} = re^{rx}, \quad \frac{d^2y}{dx^2} = r^2e^{rx}.$$

Substituting from (1) and (2) in (G) and dividing out the factor e^{rx} , the result is

$$(3) \quad r^2 + pr + q = 0,$$

a quadratic equation whose roots are the values of r required. Equation (3) is called the **auxiliary equation** for (G). If (3) has distinct roots r_1 and r_2 , then

$$(4) \quad y = e^{r_1x} \quad \text{and} \quad y = e^{r_2x}$$

are distinct particular solutions of (G), and the complete solution is

$$(5) \quad y = c_1e^{r_1x} + c_2e^{r_2x}.$$

In fact, (5) contains two essential arbitrary constants, and (G) is satisfied by this relation.

ILLUSTRATIVE EXAMPLE 1. Solve

$$(6) \quad \frac{d^2y}{dx^2} - 2 \frac{dy}{dx} - 3y = 0.$$

Solution. The auxiliary equation is

$$(7) \quad r^2 - 2r - 3 = 0.$$

Solving (7), the roots are 3 and -1 , and by (5) the complete solution is

$$y = c_1e^{3x} + c_2e^{-x}. \quad \text{Ans.}$$

Check. Substituting this value of y in (6), the equation is satisfied.

Roots of (3) imaginary. If the roots of the auxiliary equation (3) are imaginary, the exponents in (5) will also be imaginary. A real complete solution may be found, however, by choosing imaginary values of c_1 and c_2 in (5). In fact, let

$$(8) \quad r_1 = a + b\sqrt{-1}, \quad r_2 = a - b\sqrt{-1}$$

be the pair of conjugate imaginary roots of (3). Then

$$(9) \quad e^{r_1x} = e^{(a+b\sqrt{-1})x} = e^{ax}e^{bx\sqrt{-1}}, \quad e^{r_2x} = e^{(a-b\sqrt{-1})x} = e^{ax}e^{-bx\sqrt{-1}}.$$

Substituting these values in (5), we obtain

$$(10) \quad y = e^{ax}(c_1 e^{bx\sqrt{-1}} + c_2 e^{-bx\sqrt{-1}}).$$

In the algebra of imaginary numbers it is shown that*

$$e^{bx\sqrt{-1}} = \cos bx + \sqrt{-1} \sin bx, \quad e^{-bx\sqrt{-1}} = \cos bx - \sqrt{-1} \sin bx.$$

When these values are substituted in (10), the complete solution may be written

$$(11) \quad y = e^{ax}(A \cos bx + B \sin bx),$$

if the new arbitrary constants A and B are determined from c_1 and c_2 by $A = c_1 + c_2$, $B = (c_1 - c_2)\sqrt{-1}$. That is, we now take for c_1 and c_2 in (5) the imaginary values $c_1 = \frac{1}{2}(A - B\sqrt{-1})$, $c_2 = \frac{1}{2}(A + B\sqrt{-1})$.

By giving to A and B in (11) the values 1 and 0, and 0 and 1, in turn, we see that

$$(12) \quad y = e^{ax} \cos bx \quad \text{and} \quad y = e^{ax} \sin bx$$

are real particular solutions of (G).

ILLUSTRATIVE EXAMPLE 2. Solve

$$(13) \quad \frac{d^2 y}{dx^2} + k^2 y = 0.$$

Solution. The auxiliary equation (3) is now

$$r^2 + k^2 = 0. \quad \therefore r = \pm k\sqrt{-1}.$$

Comparing with (8), we see that $a = 0$, $b = k$. Hence, by (11), the complete solution is

$$y = A \cos kx + B \sin kx.$$

Check. When this value of y is substituted in (13), the equation is satisfied. Compare this method with that used for the same example in Art. 205 ($k = a$).

REMARK. A different form for the solution is obtained by setting $A = C \cos \alpha$, $B = C \sin \alpha$ in the above value of y . Then $y = C \cos(kx - \alpha)$. (By (4), p. 3).

* Let $i = \sqrt{-1}$, and assume that the series for e^x in Problem 1, Art. 194, represents the function when x is replaced by ibx . Then, since $i^2 = -1$, $i^3 = -i$, $i^4 = 1$, etc., we have

$$(14) \quad e^{ibx} = 1 + ibx - \frac{b^2 x^2}{[2]} - i \frac{b^3 x^3}{[3]} + \frac{b^4 x^4}{[4]} + i \frac{b^5 x^5}{[5]} - \dots$$

Also, replacing x by bx in (7) and (8), Art. 194,

$$\cos bx = 1 - \frac{b^2 x^2}{[2]} + \frac{b^4 x^4}{[4]} - \dots, \quad \sin bx = bx - \frac{b^3 x^3}{[3]} + \frac{b^5 x^5}{[5]} - \dots$$

Then, by Art. 195,

$$(15) \quad \cos bx + i \sin bx = 1 + ibx - \frac{b^2 x^2}{[2]} - i \frac{b^3 x^3}{[3]} + \frac{b^4 x^4}{[4]} + i \frac{b^5 x^5}{[5]} - \dots,$$

assuming that the series represents the function. The right-hand members of (14) and (15) are identical. Therefore $e^{ibx} = \cos bx + i \sin bx$

Roots of (3) real and equal. The roots of the auxiliary equation (3) will be equal if $p^2 = 4q$. Then (3) may be written, by substituting $q = \frac{1}{4} p^2$,

$$(14) \quad r^2 + pr + \frac{1}{4} p^2 = (r + \frac{1}{2} p)^2 = 0,$$

and $r_1 = r_2 = -\frac{1}{2} p$. In this case

$$(15) \quad y = e^{r_1 x} \quad \text{and} \quad y = x e^{r_1 x}$$

are distinct particular solutions, and

$$(16) \quad y = e^{r_1 x} (c_1 + c_2 x)$$

is the complete solution.

To corroborate this statement, it is only necessary to prove that the second equation in (15) gives a solution. But we have, by differentiating,

$$(17) \quad y = x e^{r_1 x}, \quad \frac{dy}{dx} = e^{r_1 x} (1 + r_1 x), \quad \frac{d^2 y}{dx^2} = e^{r_1 x} (2 r_1 + r_1^2 x).$$

Substituting from (17) into the left-hand member of (G), the result is, after canceling $e^{r_1 x}$,

$$(18) \quad (r_1^2 + p r_1 + q)x + 2 r_1 + p.$$

This vanishes, since r_1 satisfies (3) and equals $-\frac{1}{2} p$.

ILLUSTRATIVE EXAMPLE 3. Solve

$$(19) \quad \frac{d^2 s}{dt^2} + 2 \frac{ds}{dt} + s = 0.$$

Find the particular solution such that

$$s = 4 \quad \text{and} \quad \frac{ds}{dt} = -2 \quad \text{when} \quad t = 0.$$

Solution. The auxiliary equation is

$$r^2 + 2r + 1 = 0, \quad \text{or} \quad (r + 1)^2 = 0.$$

Hence the roots are equal, $r_1 = -1$, and, by (16),

$$(20) \quad s = e^{-t} (c_1 + c_2 t).$$

This is the complete solution.

To find the required particular solution, we must find values for the constants c_1 and c_2 such that the given conditions,

$$s = 4 \quad \text{and} \quad \frac{ds}{dt} = -2 \quad \text{when} \quad t = 0$$

are satisfied.

Substituting in the complete solution (20) the given values $s = 4$, $t = 0$, we have $4 = c_1$, and hence

$$(21) \quad s = e^{-t} (4 + c_2 t).$$

Now differentiate (21) with respect to t . We get

$$\frac{ds}{dt} = e^{-t}(c_2 - 4 - c_2 t).$$

By the given conditions, $\frac{ds}{dt} = -2$ when $t = 0$.

Substituting, the result is $-2 = c_2 - 4$, and hence $c_2 = 2$. Then the particular solution required is $s = e^{-t}(4 + 2t)$. *Ans.*

PROBLEMS

Find the complete solution of each of the following differential equations.

1. $\frac{d^2x}{dt^2} - \frac{dx}{dt} - 2x = 0$. *Ans.* $x = c_1 e^{-t} + c_2 e^{2t}$.
2. $\frac{d^2y}{dx^2} - 4\frac{dy}{dx} + 3y = 0$. $y = c_1 e^x + c_2 e^{3x}$.
3. $\frac{d^2s}{dt^2} - 2\frac{ds}{dt} + s = 0$. $s = c_1 e^t + c_2 t e^t$.
4. $\frac{d^2x}{dt^2} + 16x = 0$. $x = c_1 \cos 4t + c_2 \sin 4t$.
5. $\frac{d^2s}{dt^2} - 4s = 0$. $s = c_1 e^{2t} + c_2 e^{-2t}$.
6. $\frac{d^2y}{dx^2} + 4\frac{dy}{dx} = 0$. $y = c_1 + c_2 e^{-4x}$.
7. $\frac{d^2s}{dt^2} + 2\frac{ds}{dt} + 2s = 0$. $s = e^{-t}(c_1 \cos t + c_2 \sin t)$.
8. $\frac{d^2s}{dt^2} - 2\frac{ds}{dt} + 5s = 0$. $s = e^t(c_1 \cos 2t + c_2 \sin 2t)$.
9. $\frac{d^2\theta}{dt^2} - 5\frac{d\theta}{dt} + 4\theta = 0$. 13. $\frac{d^2s}{dt^2} - 3s = 0$.
10. $\frac{d^2y}{dx^2} + 6\frac{dy}{dx} + 9y = 0$. 14. $\frac{d^2y}{dx^2} - n\frac{dy}{dx} = 0$.
11. $\frac{d^2y}{dx^2} + 5\frac{dy}{dx} + 6y = 0$. 15. $\frac{d^2s}{dt^2} - 6\frac{ds}{dt} + 25s = 0$.
12. $\frac{d^2s}{dt^2} + 3s = 0$. 16. $\frac{d^2x}{dt^2} + 2\frac{dx}{dt} + 10x = 0$.

In the following problems find the particular solution which satisfies the given conditions.

17. $\frac{d^2s}{dt^2} + 3\frac{ds}{dt} + 2s = 0$; $s = 0$, $\frac{ds}{dt} = 1$, when $t = 0$. *Ans.* $s = e^{-t} - e^{-2t}$.
18. $\frac{d^2x}{dt^2} + n^2x = 0$; $x = a$, $\frac{dx}{dt} = 0$, when $t = 0$. $x = a \cos nt$.

$$19. \frac{d^2x}{dt^2} - n^2x = 0; x = 2, \frac{dx}{dt} = 0, \text{ when } t = 0. \quad \text{Ans. } x = e^{nt} + e^{-nt}.$$

$$20. \frac{d^2y}{dt^2} + 2 \frac{dy}{dt} - 8y = 0; y = 0, \frac{dy}{dt} = 24, \text{ when } t = 0. \quad \text{Ans. } y = 4(e^{2t} - e^{-4t}).$$

$$21. \frac{d^2s}{dt^2} - 8 \frac{ds}{dt} + 16s = 0; s = 0, \frac{ds}{dt} = 1, \text{ when } t = 0. \quad s = te^{4t}.$$

$$22. \frac{d^2x}{dt^2} - a \frac{dx}{dt} = 0; x = 0, \frac{dx}{dt} = a, \text{ when } t = 0. \quad x = e^{at} - 1.$$

$$23. \frac{d^2s}{dt^2} + 8 \frac{ds}{dt} + 25s = 0; s = 4, \frac{ds}{dt} = -16, \text{ when } t = 0. \quad \text{Ans. } s = 4e^{-4t} \cos 3t.$$

$$24. \frac{d^2x}{dt^2} - 6 \frac{dx}{dt} + 10x = 0; x = 1, \frac{dx}{dt} = 4, \text{ when } t = 0. \quad \text{Ans. } x = e^{3t}(\cos t + \sin t).$$

$$25. \frac{d^2s}{dt^2} + 4s = 0; s = 0, \frac{ds}{dt} = 4, \text{ when } t = 0.$$

$$26. \frac{d^2x}{dt^2} - 4x = 0; x = 10, \frac{dx}{dt} = 0, \text{ when } t = 0.$$

$$27. \frac{d^2y}{dt^2} + 4 \frac{dy}{dt} = 0; y = 1, \frac{dy}{dt} = 2, \text{ when } t = 0.$$

$$28. \frac{d^2x}{dt^2} - 4 \frac{dx}{dt} + 4x = 0; x = 2, \frac{dx}{dt} = 5, \text{ when } t = 0.$$

$$29. \frac{d^2x}{dt^2} - 4 \frac{dx}{dt} + 13x = 0; x = 2, \frac{dx}{dt} = 4, \text{ when } t = 0.$$

$$30. \frac{d^2s}{dt^2} + 4 \frac{ds}{dt} + 8s = 0; s = 0, \frac{ds}{dt} = 8, \text{ when } t = 0.$$

To solve the differential equation

$$(H) \quad \frac{d^2y}{dx^2} + p \frac{dy}{dx} + qy = X,$$

where p and q are constants and X is a function of the independent variable x or a constant, three steps are necessary.

FIRST STEP. Solve the equation (G). Let the complete solution be

$$(22) \quad y = u.$$

Then u is called the **complementary function** for (H).

SECOND STEP. Obtain a particular solution

$$(23) \quad y = v$$

of (H) by trial.

THIRD STEP. The complete solution of (H) is now

$$(24) \quad y = u + v.$$

In fact, when the value of y from (24) is substituted in (H), it is seen that the equation is satisfied, and (24) contains two essential arbitrary constants.

To determine the particular solution (23), the following directions are useful (see also Art. 208). In the formulas all letters except x , the independent variable, are constants.

General case. If $y = X$ is not a particular solution of (G), if

Form of X

Form of v

$$X = a + bx,$$

$$\text{assume } y = v = A + Bx;$$

$$X = ae^{bx},$$

$$\text{assume } y = v = Ae^{bx};$$

$$X = a_1 \cos bx + a_2 \sin bx, \quad \text{assume } y = v = A_1 \cos bx + A_2 \sin bx.$$

Special case. If $y = X$ is a particular solution of (G), assume for v the above form multiplied by x (the independent variable).

The method consists in substituting $y = v$, as given above, in (H), and determining the constants A, B, A_1, A_2 , so that (H) is satisfied.

ILLUSTRATIVE EXAMPLE 4. Solve

$$(25) \quad \frac{d^2y}{dx^2} - 2 \frac{dy}{dx} - 3y = 2x.$$

Solution. First Step. The complementary function u is found from the complete solution of

$$(26) \quad \frac{d^2y}{dx^2} - 2 \frac{dy}{dx} - 3y = 0.$$

By Illustrative Example 1, above, therefore

$$(27) \quad y = u = c_1 e^{1x} + c_2 e^{-2x}.$$

Second Step. Since $y = X = 2x$ is not a particular solution of (26), assume for a particular solution of (25)

$$(28) \quad y = v = A + Bx.$$

Substituting this value in (25) and collecting terms, the result is

$$(29) \quad -2B - 3A - 3Bx = 2x.$$

Equating coefficients of like powers of x , we get

$$-2B - 3A = 0, \quad -3B = 2.$$

Solving, $A = \frac{2}{3}$, $B = -\frac{2}{3}$, and substituting in (28), we obtain the particular solution

$$(30) \quad y = v = \frac{2}{3} - \frac{2}{3}x.$$

Third Step. Then, from (27) and (30), the complete solution is

$$y = u + v = c_1 e^{1x} + c_2 e^{-2x} + \frac{2}{3} - \frac{2}{3}x. \quad \text{Ans.}$$

ILLUSTRATIVE EXAMPLE 5. Solve

$$(31) \quad \frac{d^2y}{dx^2} - 2 \frac{dy}{dx} - 3y = 2e^{-x}.$$

Solution. *First Step.* The complementary function is (27), or

$$(32) \quad y = u = c_1 e^{3x} + c_2 e^{-x}.$$

Second Step. Here $y = X = 2e^{-x}$ is a particular solution of (26), for it is obtained from the complete solution (32) by letting $c_1 = 0$, $c_2 = 2$. Hence assume for a particular solution v of (31),

$$(33) \quad y = v = Axe^{-x}.$$

Differentiating (33), we obtain

$$(34) \quad \frac{dy}{dx} = Ae^{-x}(1-x), \quad \frac{d^2y}{dx^2} = Ae^{-x}(x-2).$$

Substituting from (33) and (34) in (31), we obtain

$$(35) \quad Ae^{-x}(x-2) - 2Ae^{-x}(1-x) - 3Axe^{-x} = 2e^{-x}.$$

Simplifying, we get $-4Ae^{-x} = 2e^{-x}$, and hence $A = -\frac{1}{2}$. Substituting in (33) we obtain

$$(36) \quad y = v = -\frac{1}{2}xe^{-x}.$$

Third Step. The complete solution of (31) is, therefore,

$$y = u + v = c_1 e^{3x} + c_2 e^{-x} - \frac{1}{2}xe^{-x}. \text{ Ans.}$$

ILLUSTRATIVE EXAMPLE 6. Determine the particular solution of

$$(37) \quad \frac{d^2s}{dt^2} + 4s = 2 \cos 2t,$$

such that $s = 0$ and $\frac{ds}{dt} = 2$ when $t = 0$.

Solution. Find the complete solution first.

First Step. Solving

$$(38) \quad \frac{d^2s}{dt^2} + 4s = 0,$$

we find the complementary function

$$(39) \quad s = u = c_1 \cos 2t + c_2 \sin 2t.$$

Second Step. Considering the right-hand member in (37), we observe that $s = 2 \cos 2t$ is a particular solution of (38) resulting from (39) when $c_1 = 2$, $c_2 = 0$. Hence for a particular solution $s = v$ of (37) assume

$$(40) \quad s = v = t(A_1 \cos 2t + A_2 \sin 2t).$$

Differentiating (40), we obtain

$$(41) \quad \begin{cases} \frac{ds}{dt} = 4_1 \cos 2t + A_2 \sin 2t - 2t(A_1 \sin 2t - A_2 \cos 2t), \\ \frac{d^2s}{dt^2} = -4A_1 \sin 2t + 4A_2 \cos 2t - 4t(A_1 \cos 2t + A_2 \sin 2t). \end{cases}$$

Substituting from (40) and (41) in (37), and simplifying, the result is

$$(42) \quad -4 A_1 \sin 2t + 4 A_2 \cos 2t = 2 \cos 2t.$$

This equation becomes an identity when $A_1 = 0$, $A_2 = \frac{1}{2}$. Substituting in (40), we get

$$(43) \quad s = r = \frac{1}{2} t \sin 2t.$$

Third Step. By (39) and (43) the complete solution of (37) is

$$(44) \quad s = c_1 \cos 2t + c_2 \sin 2t + \frac{1}{2} t \sin 2t.$$

We must now determine c_1 and c_2 so that

$$(45) \quad s = 0 \text{ and } \frac{ds}{dt} = 2 \text{ when } t = 0.$$

Differentiating (44),

$$(46) \quad \frac{ds}{dt} = -2c_1 \sin 2t + 2c_2 \cos 2t + \frac{1}{2} \sin 2t + t \cos 2t.$$

Substituting the given conditions (45) in (44) and (46), the results are

$$0 = c_1, \quad 2 = 2c_2. \quad \therefore c_1 = 0, \quad c_2 = 1.$$

Putting these values back in (44), the particular solution required is

$$(47) \quad s = \sin 2t + \frac{1}{2} t \sin 2t. \quad \text{Ans.}$$

PROBLEMS

Find the complete solution of each of the following differential equations.

$$1. \quad \frac{d^2x}{dt^2} + x = at + b. \quad \text{Ans. } x = c_1 \cos t + c_2 \sin t + at + b.$$

$$2. \quad \frac{d^2x}{dt^2} + x = ae^{bt}. \quad x = c_1 \cos t + c_2 \sin t + \frac{ae^{bt}}{b^2 + 1}.$$

$$3. \quad \frac{d^2x}{dt^2} + x = 4 \cos t. \quad x = c_1 \cos t + c_2 \sin t + 2t \sin t.$$

$$4. \quad \frac{d^2x}{dt^2} + x = 4 \sin 2t. \quad x = c_1 \cos t + c_2 \sin t - \frac{1}{3} \sin 2t.$$

$$5. \quad \frac{d^2s}{dt^2} - 4s = at + b. \quad s = c_1 e^{2t} + c_2 e^{-2t} - \frac{1}{4}(at + b).$$

$$6. \quad \frac{d^2s}{dt^2} - 4s = 2e^t. \quad s = c_1 e^{2t} + c_2 e^{-2t} - \frac{2}{3} e^t.$$

$$7. \quad \frac{d^2s}{dt^2} - 4s = e^{2t}. \quad s = c_1 e^{2t} + c_2 e^{-2t} + \frac{1}{4} t e^{2t}.$$

$$8. \quad \frac{d^2s}{dt^2} - 4s = 2 \cos 2t. \quad s = c_1 e^{2t} + c_2 e^{-2t} - \frac{1}{4} \cos 2t.$$

$$9. \quad \frac{d^2y}{dx^2} + 9y = 5x^2. \quad y = c_1 \cos 3x + c_2 \sin 3x + \frac{5}{9} x^2 - \frac{1}{81}.$$

Ans. $x = \frac{1}{9}(e^{3t} + e^{-t} - 6t + 1)$.

32. $\frac{d^2x}{dt^2} - 6 \frac{dx}{dt} + 13x = 39$; $x = 4$, $\frac{dx}{dt} = 3$, when $t = 0$.
Ans. $x = e^{3t} \cos 2t + 3$.
33. $\frac{d^2s}{dt^2} + 9s = 4 - 3t$; $s = 0$, $\frac{ds}{dt} = 0$, when $t = 0$.
34. $\frac{d^2s}{dt^2} - 9s = 6t$; $s = 0$, $\frac{ds}{dt} = 0$, when $t = 0$.
35. $\frac{d^2y}{dx^2} - 2 \frac{dy}{dx} = 2x$; $y = 2$, $\frac{dy}{dx} = 0$, when $x = 0$.
36. $\frac{d^2x}{dt^2} + x = 2 \cos 2t$; $x = 0$, $\frac{dx}{dt} = 2$, when $t = 0$.
37. $\frac{d^2s}{dt^2} + 4s = 2 \cos 2t$; $s = 0$, $\frac{ds}{dt} = 2$, when $t = 0$.
38. $\frac{d^2x}{dt^2} - 2 \frac{dx}{dt} + 2x = 2 \sin t$; $x = 0$, $\frac{dx}{dt} = 0$, when $t = 0$.
39. $\frac{d^2y}{dx^2} + 5 \frac{dy}{dx} + 4y = 2e^x$; $y = 1$, $\frac{dy}{dx} = 0$, when $x = 0$.
40. $\frac{d^2y}{dx^2} + 4 \frac{dy}{dx} + 4y = 4e^{2x}$; $y = 0$, $\frac{dy}{dx} = 2$, when $x = 0$.

207. Applications. Compound-interest law. A simple application of differential equations is afforded by problems in which the rate of change of the function with respect to the variable (Art. 50) for any value of the variable is proportional to the corresponding value of the function. That is, if $y = f(x)$,

$$(1) \quad \frac{dy}{dx} = ky,$$

where k is a constant. In this differential equation the variables are separable as in Type I, p. 379. Solving, we get

$$(2) \quad y = ce^{kx},$$

where c is an arbitrary constant. Thus the function y is an exponential function (Art. 62). Conversely, given (2), it is easily shown by differentiation that y satisfies (1). The connection of (1) with the name "compound-interest law" is shown as follows:

Let y = a sum of money in dollars accumulating at compound interest;

i = interest in dollars on one dollar for a year;

Δt = an interval of time measured in years;

Δy = the interest of y dollars for the interval of time Δt .

Then $\Delta y = iy \Delta t$. Therefore

$$(3) \quad \frac{\Delta y}{\Delta t} = iy.$$

Equation (3) states that the average rate of change of y (Art. 50) for the period of time Δt is proportional to y itself. In business, interest is added to the principal at stated times only, — yearly, quarterly, etc. In other words, y changes dis-

continuously with t . But in nature, changes proceed on the whole in a continuous manner. So that to adapt equation (3) to natural phenomena we must imagine the sum y to accumulate continuously; that is, assume the interval of time Δt to be infinitesimal. Then equation (3) becomes

$$\frac{dy}{dt} = iy,$$

and the rate of change of y is proportional to y , agreeing with (1) if $k = i$.

In (1) the function y is said to change according to the compound-interest law.

A second example is afforded by the complete solution of the equation

$$(4) \quad \frac{dy}{dx} = ky + c,$$

where k and c are constants not equal to zero. For let $c = ak$. Then (4) may be written

$$(5) \quad \frac{d}{dx}(y + a) = k(y + a).$$

This equation states that the function $y + a$ changes according to the compound-interest law. The differential equation (4), or (5), is solved as in Type I, p. 379. The solution is

$$(6) \quad y = ce^{kx} - a.$$

ILLUSTRATIVE EXAMPLE 1. The function y of x changes according to the compound-interest law. When $x = 1$, $y = 4$; when $x = 2$, $y = 12$. Find the law.

Solution. By (1) we have

$$(7) \quad \frac{dy}{dx} = ky.$$

Separating the variables and integrating, we get

$$\ln y = kx + C.$$

We have to find the values of k and C . Substitute the given values of x and y . Then

$$\ln 4 = k + C, \quad \ln 12 = 2k + C.$$

Solving, $k = \ln 12 - \ln 4 = \ln 3 = 1.0986$, $C = \ln 4 - \ln 3 = \ln \frac{4}{3}$.

Therefore $\ln y = 1.0986x + \ln \frac{4}{3}$, and $y = \frac{4}{3}e^{1.0986x}$. *Ans.*

ILLUSTRATIVE EXAMPLE 2. *Washing down a solution.* Water is run into a tank containing a saline (or acid) solution with the purpose of reducing its strength. The volume r of the mixture in the tank is kept constant. If s = quantity of salt (or acid) in the tank at any time, and x = amount of water which has run through, show that the rate of decrease of s with respect to x varies as s , and, in fact, that

$$\frac{ds}{dx} = -\frac{s}{r}.$$

Solution. Since s = quantity of salt in the mixture of total volume r , the quantity of salt in any other volume u of the mixture is $\frac{s}{r}u$.

Suppose a volume Δx of the mixture is dipped out of the tank. The amount of salt thus dipped out will be $\frac{s}{v} \Delta x$, and hence the change in the amount of salt in the tank is given by

$$(8) \quad \Delta s = -\frac{s}{v} \Delta x.$$

Suppose now that a volume of water Δx is added to fill the tank to its original volume v . Then from (8) the ratio of the amount of salt removed to the volume of water added is given by

$$\frac{\Delta s}{\Delta x} = -\frac{s}{v}.$$

When $\Delta x \rightarrow 0$ we obtain the instantaneous rate of change of s with respect to x , namely,

$$\frac{ds}{dx} = -\frac{s}{v}. \quad \text{Ans.}$$

Hence s changes according to the compound-interest law.

PROBLEMS

1. The rate of change of a function y with respect to x equals $\frac{1}{3}y$, and $y = 4$ when $x = -1$. Find the law connecting x and y . *Ans.* $y = 5.58 e^{\frac{1}{3}x}$.

2. The rate of change of a function y with respect to x equals $2 - y$, and $y = 8$ when $x = 0$. Find the law. *Ans.* $y = 6e^{-x} + 2$.

3. In Illustrative Example 2, if $v = 10,000$ gal., how much water must be run through to wash down 50 per cent of the salt? *Ans.* 6931 gal.

4. *Newton's law of cooling.* If the excess temperature of a body above the temperature of the surrounding air is x degrees, the time-rate of decrease of x is proportional to x . If this excess temperature was at first 80 degrees, and after 1 min. is 70 degrees, what will it be after 2 min.? In how many minutes will it decrease 20 degrees?

5. Atmospheric pressure p at points above the earth's surface as a function of the altitude h above sea level changes according to the compound-interest law. Assuming $p = 15$ lb. per sq. in. when $h = 0$, and 10 lb. when $h = 10,000$ ft., find p (a) when $h = 5000$ ft.; (b) when $h = 15,000$ ft. *Ans.* (a) 12.2 lb.; (b) 8.15 lb.

6. The velocity of a chemical reaction in which x is the amount transformed in time t is the time-rate of change of x .

Reaction of the first order. Let a = concentration at the beginning of the experiment. Then $\frac{dx}{dt} = k(a - x)$, since the rate of change is proportional to the concentration at that instant. (Note that $a - x$, the concentration, changes according to the compound-interest law.)

Prove that k , the velocity constant, is equal to $\frac{1}{t} \ln \frac{a}{a-x}$.

7. In the inversion of raw sugar, the time-rate of change varies as the amount of raw sugar remaining. If, after 10 hr., 1000 lb. of raw sugar have been reduced to 800 lb., how much raw sugar will remain at the expiration of 24 hr.? *Ans.* 586 lb.

8. In an electric circuit with given voltage E and current i (amperes), the voltage E is consumed in overcoming (1) the resistance R (ohms) of the circuit, and (2) the inductance L , the equation being

$$E = Ri + L \frac{di}{dt}, \quad \text{or} \quad \frac{di}{dt} = \frac{1}{L} (E - Ri).$$

This process therefore comes under equation (4) above, E , R , L being constants. Given $L = 640$, $R = 250$, $E = 500$, and $i = 0$ when $t = 0$, show that the current will approach 2 amperes as t increases. Also find in how many seconds i will reach 90 per cent of its maximum value. *Ans.* 5.9 sec.

9. In a condenser discharging electricity, the time-rate of change of the voltage c is proportional to c , and c decreases with the time. Given $k = 40$, find t if c decreases to 10 per cent of its original value. *Ans.* 92 sec.

10. Building up a saline (or acid) solution by adding salt (or acid), maintaining constant volume, leads to the equation $\frac{dy}{dx} = \frac{1}{r} (r - y)$, where $r =$ the constant volume, $y =$ salt (or acid) in the tank at any moment, $x =$ salt (or acid) added from the beginning. Derive this result and compare with Illustrative Example 2 above.

208. Applications to problems in mechanics. Many important problems in mechanics and physics are solved by the methods explained in this chapter. For example, problems in rectilinear motion often lead to differential equations of the first or second order, and the solution of the problems depends upon solving these equations.

Before giving illustrative examples it is to be recalled (Arts. 51 and 59) that

$$(1) \quad v = \frac{ds}{dt}, \quad a = \frac{d^2s}{dt^2} = \frac{dv}{dt} = v \frac{dv}{ds},$$

where v and a are, respectively, the velocity and acceleration at any instant of time ($= t$), and s equals the distance of the moving point at this time from a fixed origin on the linear path.

ILLUSTRATIVE EXAMPLE 1. In a rectilinear motion the acceleration is inversely proportional to the square of the distance s , and equals -1 when $s = 2$. That is,

$$(2) \quad \text{Acceleration} = a = -\frac{4}{s^2}.$$

Also, $v = 5$, $s = 8$, when $t = 0$.

(a) Find v when $s = 24$.

Solution. From (2), using the last form for a , we obtain

$$(3) \quad v \frac{dv}{ds} = -\frac{4}{s^2}.$$

Multiplying both members by ds and integrating, the result is

$$(4) \quad \frac{v^2}{2} = \frac{4}{s} + C, \quad \text{or} \quad v^2 = \frac{8}{s} + C'.$$

Substituting in (4) the above conditions $r = 5$, $s = 8$, we find $v = 24$. Hence (4) becomes

$$(5) \quad r^2 = \frac{s}{s} + 24.$$

From this equation, if $s = 24$, $r = \frac{1}{3} \sqrt{219} = 4.93$. *Ans.*

(b) Find the time which elapses when the point moves from $s = 8$ to $s = 24$.

Solution. Solving (5) for r , we get

$$(6) \quad \frac{ds}{dt} = r = \sqrt{8} \frac{\sqrt{s+3s^2}}{s}.$$

Separating the variables s and t and solving for t with limits as given, $s = 8$, $s = 24$, we find, for the elapsed time,

$$(7) \quad t = \frac{1}{2\sqrt{2}} \int_8^{24} \frac{s ds}{\sqrt{s+3s^2}} = 3.23. \quad \text{Ans.}$$

NOTE. Using the first form in (1) for a , (2) is

$$\frac{d^2s}{dt^2} = -\frac{4}{s^3},$$

which is of the form (F), Art. 205. The method of integration here is the same as in Art. 205.

An important type of rectilinear motion is that in which the acceleration and the distance are in a constant ratio and differ in sign. Then we may write

$$(8) \quad a = -k^2s,$$

where $k^2 = \text{magnitude of } a \text{ at unit distance}$.

Remembering that a force and the acceleration caused by it differ in magnitude only, we see in the above case that the effective force is directed always toward the point $s = 0$ and is, in magnitude, directly proportional to the distance s . The motion is called *simple harmonic vibration*.

From (8), we have, using (1),

$$(9) \quad \frac{d^2s}{dt^2} + k^2s = 0,$$

a linear equation in s and t of the second order with constant coefficients. Integrating (see Illustrative Example 2, Art. 206), we obtain the complete solution,

$$(10) \quad s = c_1 \cos kt + c_2 \sin kt.$$

From (10), by differentiation,

$$(11) \quad v = k(-c_1 \sin kt + c_2 \cos kt).$$

It is easy to see that the motion defined by (10) is a periodic oscillation between the extreme positions $s = b$, and $s = -b$, determined by

$$(12) \quad b = \sqrt{c_1^2 + c_2^2}, \quad \text{period} = \frac{2\pi}{k}.$$

In fact, we may replace the constants c_1 and c_2 in (10) by other constants b and A , such that

$$(13) \quad c_1 = b \sin A, \quad c_2 = b \cos A.$$

Substituting these values in (10), it reduces to

$$(14) \quad s = b \sin (kt + A), \quad \text{by (4), Art. 2}$$

and now the truth of the above statement is manifest.

In the following examples we give cases when the simple harmonic motion is disturbed by other forces. In all cases the problem depends upon the solution of an equation of the form (G) and (H), discussed above.

ILLUSTRATIVE EXAMPLE 2. In a rectilinear motion

$$(15) \quad a = -\frac{5}{4}s - v.$$

Also, $v = 2$, $s = 0$, when $t = 0$.

(a) Find the equation of motion (s in terms of t).

Solution. Using (1), we have, from (15),

$$(16) \quad \frac{d^2s}{dt^2} + \frac{ds}{dt} + \frac{5}{4}s = 0,$$

an equation of the form (G). The roots of the auxiliary equation $r^2 + r + \frac{5}{4} = 0$ are

$$r_1 = -\frac{1}{2} + \sqrt{-1}, \quad r_2 = -\frac{1}{2} - \sqrt{-1}.$$

Hence the complete solution of (16) is

$$(17) \quad s = e^{-\frac{1}{2}t}(c_1 \cos t + c_2 \sin t).$$

By the given conditions, $s = 0$ when $t = 0$. Substituting these values in (17), we find $c_1 = 0$, and hence

$$(18) \quad s = c_2 e^{-\frac{1}{2}t} \sin t.$$

Differentiating to find v , we get

$$(19) \quad v = c_2 e^{-\frac{1}{2}t}(-\frac{1}{2} \sin t + \cos t).$$

Substituting the given values $v = 2$ when $t = 0$, we have $2 = c_2$.

With this value of c_2 , (18) becomes

$$(20) \quad s = 2 e^{-\frac{1}{2}t} \sin t. \quad \text{Ans.}$$

(b) For what values of t will $v = 0$?

Solution. When $v = 0$, the expression in the parenthesis of the right-hand member of (19) must vanish. Setting this equal to zero, we readily obtain

$$(21) \quad \tan t = 2.$$

For any value of t satisfying (21), v will vanish. These values are

$$(22) \quad t = 1.10 + n\pi. \quad (n = \text{an integer}). \quad \text{Ans.}$$

Successive values of t from (22) differ by the constant interval of time π .

Discussion. This example illustrates *damped harmonic vibration*. In fact, in (15) the acceleration is the sum of two components

$$(23) \quad a_1 = -\frac{5}{4}s, \quad a_2 = -v.$$

The simple harmonic vibration corresponding to the component a_1 is now disturbed by a *damping force* with the acceleration a_2 , that is, by a force proportional to the velocity and opposite to the direction of motion. The effects of this damping force are twofold.

First, the interval of time between successive positions of the point where $v = 0$ is *lengthened* by the damping force. In fact, for the simple harmonic vibration

$$(24) \quad a_1 = -\frac{5}{4}s,$$

we have, by comparison with (8), $k = \frac{1}{2} \sqrt{5} = 1.12$, and the half-period, by (12), is 0.89π . As we have seen above, for the damped harmonic vibration the corresponding interval is π .

Second, the values of s for the successive extreme positions where $v = 0$, instead of being equal, now form a decreasing geometric progression. Proof is omitted.

ILLUSTRATIVE EXAMPLE 3. In a rectilinear motion

$$(25) \quad a = -4s + 2 \cos 2t.$$

Also, $s = 0$, $v = 2$, when $t = 0$.

(a) Find the equation of motion.

Solution. By (1), we have, from (25),

$$(26) \quad \frac{d^2s}{dt^2} + 4s = 2 \cos 2t.$$

The particular solution required was found in Illustrative Example 6, Art. 206, and is given by equation (47), p. 397. Hence

$$(27) \quad s = \sin 2t + \frac{1}{2}t \sin 2t. \text{ Ans.}$$

(b) For what values of t will $v = 0$?

Solution. Differentiating (27) to find v , and setting the result equal to zero, we get

$$(28) \quad (2 + t) \cos 2t + \frac{1}{2} \sin 2t = 0;$$

or, dividing (28) through by $\cos 2t$,

$$(29) \quad \frac{1}{2} \tan 2t + 2 + t = 0.$$

The roots of this equation may be found as explained in Arts. 87-89. The figure shows the curves (see Art. 88)

$$(30) \quad y = \frac{1}{2} \tan 2t, \quad y = -2 - t,$$

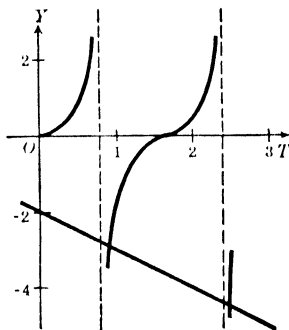
and the abscissas of the points of intersection are, approximately,

$$t = 0.88, 2.36, \text{ etc. Ans.}$$

Discussion. This example illustrates *forced harmonic vibration*. In fact, in (25) the acceleration is the sum of two components

$$(31) \quad a_1 = -4s, \quad a_2 = 2 \cos 2t.$$

The simple harmonic vibration corresponding to the component a_1 with the period π is now disturbed by a force with the acceleration a_2 , that is, by a periodic



force whose period ($= \pi$) is the same as the period of the undisturbed simple harmonic vibration. The effects of this disturbing force are twofold.

First, the interval of time between successive positions of the point where $v = 0$ is no longer constant, but decreases and approaches $\frac{1}{2} \pi$. This is clear from the above figure.

Second, the values of s for the successive extreme positions where $v = 0$ now increase and eventually become, in numerical value, indefinitely great.

PROBLEMS

In each of the following problems the acceleration and initial conditions are given. Find the equation of motion.

1. $a = -k^2 s$; $s = 0, v = v_0$, when $t = 0$. *Ans.* $s = \frac{v_0}{k} \sin kt$.

2. $a = -k^2 s$; $s = s_0, v = 0$, when $t = 0$. $s = s_0 \cos kt$.

3. $a = -k^2 s$; $s = s_0, v = v_0$, when $t = 0$.

4. $a = 6 - s$; $s = 0, v = 0$, when $t = 0$. $s = 6(1 - \cos t)$.

5. $a = \sin 2t - s$; $s = 0, v = 0$, when $t = 0$. $s = \frac{2}{3} \sin t - \frac{1}{3} \sin 2t$.

6. $a = 2 \cos t - s$; $s = 2, v = 0$, when $t = 0$. $s = 2 \cos t + t \sin t$.

7. $a = -2v - 2s$; $s = 3, v = -3$, when $t = 0$. $s = 3e^{-t} \cos t$.

8. $a = -k^2 s + b$; $s = 0, v = 0$, when $t = 0$.

9. $a = -nv$; $s = 0, v = n$, when $t = 0$.

10. $a = 8t - 4s$; $s = 0, v = 4$, when $t = 0$.

11. $a = 4 \sin t - 4s$; $s = 0, v = 0$, when $t = 0$.

12. $a = 2 \sin 2t - 4s$; $s = 0, v = 0$, when $t = 0$.

13. $a = -2v - 5s$; $s = 1, v = 1$, when $t = 0$.

14. Given $a = 8 - 4s$, and $v = 0, s = 0$, when $t = 0$. Show that the motion is a simple harmonic vibration with the center at $s = 2$, with an amplitude 2 and a period π .

15. The acceleration of a particle is given by

$$a = 5 \cos 2t - 9s.$$

(a) If the particle starts from rest at the origin, find its equation of motion. *Ans.* $s = \cos 2t - \cos 3t$.

What is the greatest distance from the origin reached by the particle?

(b) If the particle starts from the origin with velocity $v = 6$, find its equation of motion. *Ans.* $s = \cos 2t + 2 \sin 3t - \cos 3t$.

What is the greatest distance from the origin reached by the particle?

16. Answer the questions of the preceding problem if the acceleration is given by

$$a = 3 \cos 3t - 9s.$$

Ans. (a) $s = \frac{1}{2} t \sin 3t$; (b) $s = \frac{1}{2} t \sin 3t + 2 \sin 3t$.

17. A body falls from rest under the action of its weight and a small resistance which varies as the velocity. Prove the following relations:

$$a = g - kv.$$

$$v = \frac{g}{k}(1 - e^{-kt}).$$

$$s = \frac{g}{k^2}(kt + e^{-kt} - 1).$$

$$ks + v + \frac{g}{k} \ln\left(1 - \frac{kv}{g}\right) = 0.$$

18. A body falls from rest a distance of 80 ft. Assuming $a = 32 - v$, find the time. Ans. 3.47 sec.

19. A boat moving in still water is subject to a retardation proportional to its velocity at any instant. Show that the velocity t sec. after the power is shut off is given by the formula $v = ce^{-kt}$, where c is the velocity at the instant the power is shut off.

20. At a certain instant a boat drifting in still water has a velocity of 4 mi. per hour. One minute later the velocity is 2 mi. per hour. Find the distance moved.

21. Under certain conditions the equation defining the swing of a galvanometer is

$$\frac{d^2\theta}{dt^2} + 2\mu\frac{d\theta}{dt} + k^2\theta = 0.$$

Show that it will not swing through the zero point if $\mu > k$. Find the complete solution if $\mu < k$.

209. Linear differential equations of the n th order with constant coefficients. The solution of the linear differential equation

$$(I) \quad \frac{d^ny}{dx^n} + p_1 \frac{d^{n-1}y}{dx^{n-1}} + p_2 \frac{d^{n-2}y}{dx^{n-2}} + \cdots + p_n y = 0,$$

in which the coefficients p_1, p_2, \dots, p_n are constants, will now be discussed.

The substitution of e^{rx} for y in the first member gives

$$(r^n + p_1 r^{n-1} + p_2 r^{n-2} + \cdots + p_n) e^{rx}.$$

This expression vanishes for all values of r which satisfy the equation

$$(1) \quad r^n + p_1 r^{n-1} + p_2 r^{n-2} + \cdots + p_n = 0;$$

and therefore for each of these values of r , e^{rx} is a solution of (I). Equation (1) is called the *auxiliary equation* of (I). We observe that the coefficients are the same in both, the exponents in (1) corresponding to the order of the derivatives in (I), and y being replaced by 1.

From the roots of the equation we may write down particular solutions of the differential equation (I). The results are those of Art. 206 extended to cases when the order exceeds two, and are proved in more advanced textbooks.

Rule to solve the equation (I)

FIRST STEP. Write down the corresponding auxiliary equation

$$(1) \quad r^n + p_1 r^{n-1} + p_2 r^{n-2} + \dots + p_n = 0.$$

SECOND STEP. Solve completely the auxiliary equation.

THIRD STEP. From the roots of the auxiliary equation write down the corresponding particular solutions of the differential equation as follows:

AXILIARY EQUATION	DIFFERENTIAL EQUATION
(a) Each distinct real root r_1	gives a particular solution $e^{r_1 x}$.
(b) Each distinct pair of imaginary roots $a \pm bi$	gives two particular solutions $e^{ax} \cos bx$, $e^{ax} \sin bx$.
(c) A multiple root occurring s times	gives s (or $2s$) particular solutions obtained by multiplying the particular solutions (a) (or (b)) by $1, x, x^2, \dots, x^{s-1}$.

FOURTH STEP. Multiply each of the n^* independent solutions thus found by an arbitrary constant and add the results. This result set equal to y gives the complete solution.

ILLUSTRATIVE EXAMPLE 1. Solve $\frac{d^3 y}{dx^3} - 3 \frac{d^2 y}{dx^2} + 4y = 0$.

Solution. Follow the above rule.

First Step. $r^3 - 3r^2 + 4 = 0$, auxiliary equation.

Second Step. Solving, the roots are $-1, 2, 2$.

Third Step. (a) The root -1 gives the solution e^{-x} .

(c) The double root 2 gives the two solutions e^{2x}, xe^{2x} .

Fourth Step. The complete solution is

$$y = c_1 e^{-x} + c_2 e^{2x} + c_3 x e^{2x}. \text{ Ans.}$$

ILLUSTRATIVE EXAMPLE 2. Solve $\frac{d^4 y}{dx^4} - 4 \frac{d^3 y}{dx^3} + 10 \frac{d^2 y}{dx^2} - 12 \frac{dy}{dx} + 5y = 0$.

Solution. Follow the above rule.

First Step. $r^4 - 4r^3 + 10r^2 - 12r + 5 = 0$, auxiliary equation.

Second Step. Solving, the roots are $1, 1, 1 \pm 2i$.

* A check on the accuracy of the work is found in the fact that the first three steps must give n independent solutions.

Third Step. (b) The pair of imaginary roots $1 \pm 2i$ gives the two solutions

$$e^x \cos 2x, e^x \sin 2x. \quad (a = 1, b = 2)$$

(c) The double root 1 gives the two solutions e^x, xe^x .

Fourth Step. The complete solution is

$$y = c_1 e^x + c_2 x e^x + c_3 e^{2x} \cos 2x + c_4 e^{2x} \sin 2x,$$

or
$$y = (c_1 + c_2 x + c_3 \cos 2x + c_4 \sin 2x) e^x. \quad \text{Ans.}$$

The linear differential equation

$$(J) \quad \frac{d^n y}{dx^n} + p_1 \frac{d^{n-1} y}{dx^{n-1}} + p_2 \frac{d^{n-2} y}{dx^{n-2}} + \cdots + p_n y = X,$$

in which p_1, p_2, \dots, p_n are constants, and X is a function of x or a constant, is solved by methods like those used in Art. 206 for equation (H). The three steps described on page 394 are to be followed here also. That is, we solve first the equation (I), obtaining

$$(2) \quad y = u,$$

the complete solution of (J). Then u is the complementary function for (J).

Next we find in any manner a particular solution of (J),

$$(3) \quad y = v.$$

Then the complete solution of (J) is

$$(4) \quad y = u + v.$$

In finding (3), methods of trial may be used analogous to those given on page 395 for $n = 2$. The rules given there for the general case apply also for any value of n . In any case we may follow the

Rule to find a particular solution of (J)

FIRST STEP. Differentiate successively the given equation (J) and obtain, either directly or by elimination, a differential equation of a higher order of Type (I).

SECOND STEP. Solving this new equation by the rule on page 408, we get its complete solution

$$y = u + v,$$

where the part u is the complementary function of (J) already found in the first step,* and v is the sum of the additional terms found.

THIRD STEP. To find the values of the constants of integration in the particular solution v , substitute

$$y = v$$

* From the method of derivation it is obvious that every solution of the original equation must also be a solution of the derived equation.

and its derivatives in the given equation (J). In the resulting identity equate the coefficients of like terms, solve for the constants of integration, and substitute their values back in

$$y = u + v,$$

giving the complete solution of (J).

This method will now be illustrated by means of examples.

NOTE. The solution of the auxiliary equation of the new derived differential equation is facilitated by observing that the left-hand member of that equation is exactly divisible by the left-hand member of the auxiliary equation used in finding the complementary function.

ILLUSTRATIVE EXAMPLE. Solve

$$(5) \quad y'' - 3y' + 2y = xe^x.$$

Solution. We first find the complementary function u . Solving

$$(6) \quad y'' - 3y' + 2y = 0,$$

the result is

$$(7) \quad y = u = c_1 e^{2x} + c_2 e^x.$$

First Step. We now differentiate (5), obtaining

$$(8) \quad y''' - 3y'' + 2y' = xe^x + e^x.$$

Subtracting (5) from (8), the result is

$$(9) \quad y''' - 4y'' + 5y' - 2y = e^x.$$

Differentiating (9), we obtain

$$(10) \quad y^{iv} - 4y''' + 5y'' - 2y' = e^x.$$

Subtracting (9) from (10), we get

$$(11) \quad y^{iv} - 5y''' + 9y'' - 7y' + 2y = 0,$$

an equation of Type (I).

Second Step. Solve (11). The auxiliary equation is

$$(12) \quad r^4 - 5r^3 + 9r^2 - 7r + 2 = 0.$$

The left-hand member must be divisible by $r^2 - 3r + 2$, since the auxiliary equation for (6) is $r^2 - 3r + 2 = 0$. In fact, we find that (12) may be written

$$(13) \quad (r^2 - 3r + 2)(r - 1)^2 = 0.$$

The roots are $r = 1, 1, 1, 2$. Hence the complete solution of (11) is

$$(14) \quad y = c_1 e^{2x} + e^x(c_2 + c_3 x + c_4 x^2).$$

Third Step. Comparing (7) and (14), we see that

$$(15) \quad y = v = e^x(c_3 x + c_4 x^2)$$

will be a particular solution of (5) for suitable values of the constants c_3 and c_4 .

Differentiating (15), we obtain

$$(16) \quad \begin{aligned} y' &= e^x(c_3 + (c_3 + 2c_4)x + c_4 x^2), \\ y'' &= e^x(2(c_3 + c_4) + (c_3 + 4c_4)x + c_4 x^2). \end{aligned}$$

Substituting in (5) from (15) and (16), dividing both members by e^x and reducing, the result is

$$(17) \quad 2c_4 - c_3 - 2c_1x = x.$$

Equating coefficients of like powers of x , we obtain $-2c_1 = 1$, $2c_4 - c_3 = 0$, whence we find $c_1 = -1$, $c_4 = -\frac{1}{2}$. Substituting these values in (15), the particular solution is

$$(18) \quad y = v = e^x \left(-x - \frac{1}{2} x^2 \right),$$

and the complete solution is

$$y = u + v = c_1 e^{2x} + c_2 e^x - e^x \left(x + \frac{1}{2} x^2 \right). \quad \text{Ans.}$$

PROBLEMS

Find the complete solution of each of the following differential equations.

$$1. \quad \frac{d^3 y}{dx^3} + 4 \frac{dy}{dx} = 0. \quad \text{Ans.} \quad y = c_1 + c_2 \cos 2x + c_3 \sin 2x.$$

$$2. \quad \frac{d^4 y}{dx^4} + 4 \frac{d^2 y}{dx^2} = 0. \quad y = c_1 + c_2 x + c_3 \cos 2x + c_4 \sin 2x.$$

$$3. \quad \frac{d^5 y}{dx^5} - \frac{dy}{dx} = 0. \quad y = c_1 + c_2 e^x + c_3 e^{-x} + c_4 \cos x + c_5 \sin x.$$

$$4. \quad \frac{d^4 s}{dt^4} + 3 \frac{d^2 s}{dt^2} - 4s = 0. \quad s = c_1 e^t + c_2 e^{-t} + c_3 \cos 2t + c_4 \sin 2t.$$

$$5. \quad \frac{d^4 y}{dx^4} - \frac{d^3 y}{dx^3} + 9 \frac{d^2 y}{dx^2} - 9 \frac{dy}{dx} = 0. \\ \text{Ans.} \quad y = c_1 + c_2 e^x + c_3 \cos 3x + c_4 \sin 3x.$$

$$6. \quad \frac{d^4 s}{dt^4} + 8 \frac{d^2 s}{dt^2} + 16s = 0. \quad \text{Ans.} \quad s = (c_1 + c_2 t) \cos 2t + (c_3 + c_4 t) \sin 2t.$$

$$7. \quad \frac{d^4 x}{dt^4} + 6 \frac{d^2 x}{dt^2} + 12 \frac{dx}{dt} + 8x = 0. \quad \text{Ans.} \quad x = e^{-2t} (c_1 + c_2 t + c_3 t^2).$$

$$8. \quad \frac{d^4 s}{dt^4} - s = t^3 + 3t. \quad \text{Ans.} \quad s = c_1 e^t + c_2 e^{-t} + c_3 \cos t + c_4 \sin t - t^3 - 3t.$$

$$9. \quad \frac{d^3 y}{dx^3} - 4 \frac{dy}{dx} = 2x^2. \quad y = c_1 + c_2 e^{2x} + c_3 e^{-2x} - \frac{1}{6} x^3 - \frac{1}{4} x.$$

$$10. \quad \frac{d^4 y}{dx^4} - \frac{d^2 y}{dx^2} = 4x. \quad y = c_1 + c_2 x + c_3 e^x + c_4 e^{-x} - \frac{2}{3} x^3.$$

$$11. \quad \frac{d^2 y}{dx^2} - 3 \frac{dy}{dx} + 2y = x e^{3x}. \quad y = c_1 e^x + c_2 e^{2x} - \frac{3}{4} e^{3x} + \frac{1}{2} x e^{3x}.$$

$$12. \quad \frac{d^2 s}{dt^2} - 9 \frac{ds}{dt} + 20s = t^2 e^{3t}. \quad \text{Ans.} \quad s = c_1 e^{4t} + c_2 e^{5t} + \frac{e^{3t}(7 + 6t + 2t^2)}{4}.$$

$$13. \quad \frac{d^2 s}{dt^2} + 4s = t \sin 2t. \\ \text{Ans.} \quad s = c_1 \cos 2t + c_2 \sin 2t + \frac{t}{8} - \frac{t \cos 2t}{32} - \frac{t^2 \sin 2t}{16}.$$

14. $\frac{d^4y}{dx^4} - 9 \frac{d^2y}{dx^2} = 0.$

15. $\frac{d^3x}{dt^3} + 8x = 0.$

16. $\frac{d^4y}{dx^4} - 13 \frac{d^2y}{dx^2} + 36y = 0.$

17. $\frac{d^4y}{dx^4} + 5 \frac{d^2y}{dx^2} - 36y = 0.$

18. $\frac{d^4s}{dt^4} + 13 \frac{d^2s}{dt^2} + 36s = 18t - 36.$

19. $\frac{d^4x}{dt^4} + 2 \frac{d^2x}{dt^2} + x = t + 2.$

20. $\frac{d^3s}{dt^3} - 2 \frac{d^2s}{dt^2} + \frac{ds}{dt} = e^t.$

MISCELLANEOUS PROBLEMS

Find the complete solution of each of the following differential equations.

1. $8\left(\frac{dy}{dt}\right)^3 = 27y.$

Ans. $y = (t + c)^{\frac{3}{2}}.$

2. $\left(\frac{dy}{dx}\right)^3 - 27y^2 = 0.$

$y = (x + c)^3.$

3. $4\left(\frac{dy}{dx}\right)^2 = 9x.$

$y = x^{\frac{1}{2}} + c.$

4. $(1 + x^2)dy = \sqrt{1 - y^2} dx.$

$\frac{y}{\sqrt{1 - y^2}} = \frac{x + c}{1 - cx}.$

5. $(x + y)dx = (x - y)dy.$

$\ln(x^2 + y^2) - 2 \arctan \frac{y}{x} = c.$

6. $\frac{dy}{dx} + y = e^{-x}.$

$y = (x + c)e^{-x}.$

7. $\frac{d^2s}{dt^2} - 4 \frac{ds}{dt} + 3s = 0.$

$s = c_1 e^t + c_2 e^{3t}.$

8. $\frac{d^2s}{dt^2} - 4 \frac{ds}{dt} + 4s = 0.$

$s = c_1 e^{2t} + c_2 t e^{2t}.$

9. $\frac{d^2s}{dt^2} - 4 \frac{ds}{dt} + 8s = 0.$

Ans. $s = e^{2t}(c_1 \cos 2t + c_2 \sin 2t).$

10. $\frac{d^2y}{dt^2} - 2 \frac{dy}{dt} - 3y = e^{2t}.$

$y = c_1 e^{3t} + c_2 e^{-t} - \frac{1}{3} e^{2t}.$

11. $\frac{d^2x}{dt^2} + k^2x = at + b.$

$x = c_1 \cos kt + c_2 \sin kt + \frac{at + b}{k^2}.$

12. $\frac{d^2x}{dt^2} + k^2x = ae^{bt}.$

$x = c_1 \cos kt + c_2 \sin kt + \frac{ae^{bt}}{b^2 + k^2}.$

13. $\frac{d^2x}{dt^2} - k^2x = a \cos kt.$

$x = c_1 e^{kt} + c_2 e^{-kt} - \frac{a}{2k^2} \cos kt.$

14. $\frac{d^2x}{dt^2} + k^2x = a \sin kt.$

$x = c_1 \cos kt + c_2 \sin kt - \frac{a}{2k} t \cos kt.$

15. $(x^2 - 2y^2)dx + 2xy dy = 0.$

$y^2 + x^2 \ln cx = 0.$

16. $\frac{dy}{dx} + \frac{4xy}{x^2 + 1} = \frac{1}{(x^2 + 1)^3}.$

$y(x^2 + 1)^2 = \arctan x + c.$

$$17. \frac{d^4 s}{dt^4} - 5 \frac{d^2 s}{dt^2} + 4 s = 0. \quad \text{Ans. } s = c_1 e^t + c_2 e^{-t} + c_3 e^{2t} + c_4 e^{-2t}.$$

$$18. \frac{d^4 s}{dt^4} + 5 \frac{d^2 s}{dt^2} + 4 s = 0.$$

$$\text{Ans. } s = c_1 \cos t + c_2 \sin t + c_3 \cos 2t + c_4 \sin 2t.$$

$$19. xy^2 dy = (x^3 + y^3) dx.$$

$$23. \frac{d^2 x}{dt^2} + 4x = e^{-t}.$$

$$20. dy + xy(1 - x^2 y^2) dx = 0.$$

$$21. \frac{d^2 x}{dt^2} - 8 \frac{dx}{dt} + 25x = 0.$$

$$24. \frac{d^2 x}{dt^2} + 4x = 6 \cos 3t.$$

$$22. \frac{d^2 x}{dt^2} + 4x = 8t + 2.$$

$$25. \frac{d^2 x}{dt^2} + 4x = 2 \cos 2t.$$

Solve each of the following differential equations by making the transformation suggested.

$$26. t^2 \frac{ds}{dt} - 2st - s^3 = 0. \quad \text{Let } s = \frac{t^2}{v}. \quad \text{Ans. } \frac{t^4}{2s^2} + \frac{t^3}{3} = c.$$

$$27. (t^2 + t)ds = (t^2 + 2st + s)dt. \quad \text{Let } s = vt. \quad \text{Ans. } s = ct(1 + t) - t.$$

$$28. (3 + 2st)s dt = (3 - 2st)t ds. \quad \text{Let } st = v.$$

$$29. (x + y)^2 \frac{dy}{dx} = 2x + 2y + 5. \quad \text{Let } x + y = v.$$

ADDITIONAL PROBLEMS

1. For a certain curve the area bounded by the curve, the x -axis, and any two ordinates is k times the length of arc intercepted between the ordinates, and the curve passes through the point $(0, k)$. Show that the curve must be a catenary.

2. The acceleration of a man dropping in a parachute from a stationary balloon is $32 - \frac{1}{8}v^2$ ft. per second per second, where v is the velocity in feet per second. If he reaches the ground in one minute, prove that the height of the balloon is a little more than 950 ft.

3. A point moving on the x -axis is subject to an acceleration directed toward the origin and proportional to its distance from the origin and to a retardation proportional to its velocity. Given that the differential equation for x is of the form

$$\frac{d^2 x}{dt^2} + m \frac{dx}{dt} + nx = 0,$$

where m and n are positive, and given the initial conditions $x = 10$, $\frac{dx}{dt} = 0$, when $t = 0$, find in each of the following cases x and $\frac{dx}{dt}$ and discuss the motion.

(a) $m = 4$, $n = 5$; (b) $m = 4$, $n = 4$; (c) $m = 4$, $n = 3$.

CHAPTER XXII

HYPERBOLIC FUNCTIONS

210. Hyperbolic sine and cosine. Certain simple expressions involving exponential functions (Art. 62) occur frequently in applied mathematics. They are called *hyperbolic functions*. The justification for this name is brought out below in Art. 215. Two of these functions, the *hyperbolic sine* and *hyperbolic cosine* of a variable v , written, respectively, $\sinh v$ and $\cosh v$, are defined by the equations

$$(A) \quad \sinh v = \frac{e^v - e^{-v}}{2}, \quad \cosh v = \frac{e^v + e^{-v}}{2},$$

where e is, as usual, the Napierian base (Art. 61). These functions are not, however, independent, for we have from (A)

$$(B) \quad \cosh^2 v - \sinh^2 v = 1.$$

$$\left[\begin{array}{l} \text{From (A), squaring, } \cosh^2 v = \frac{e^{2v} + 2 + e^{-2v}}{4}, \quad \sinh^2 v = \frac{e^{2v} - 2 + e^{-2v}}{4}. \\ \text{Hence, by subtraction, } \cosh^2 v - \sinh^2 v = 1. \end{array} \right]$$

From (A), by solving for the exponential functions, we get

$$(1) \quad e^v = \cosh v + \sinh v, \quad e^{-v} = \cosh v - \sinh v.$$

ILLUSTRATIVE EXAMPLE. Show that the complete solution of the differential equation

$$(2) \quad \frac{d^2 y}{dx^2} - a^2 y = 0$$

may be written $y = A \sinh ax + B \cosh ax$,

where A and B are constants.

Solution. By Art. 206 the auxiliary equation for (2) is $r^2 - a^2 = 0$, whose roots are a and $-a$. Therefore the complete solution of (2) is

$$y = c_1 e^{ax} + c_2 e^{-ax}.$$

The values of e^{ax} and e^{-ax} are found from (1) by taking $v = ax$. Hence

$$\begin{aligned} e^{ax} &= \cosh ax + \sinh ax, \quad e^{-ax} = \cosh ax - \sinh ax, \\ y &= c_1 (\cosh ax + \sinh ax) + c_2 (\cosh ax - \sinh ax) \\ &= (c_1 + c_2) \cosh ax + (c_1 - c_2) \sinh ax. \end{aligned}$$

Letting $c_1 + c_2 = A$, $c_1 - c_2 = B$, we obtain the desired form.

The result should be compared with Illustrative Example 2, p. 391.

211. Other hyperbolic functions. The *hyperbolic tangent*, $\tanh v$, is defined by

$$(C) \quad \tanh v = \frac{\sinh v}{\cosh v} = \frac{e^v - e^{-v}}{e^v + e^{-v}}.$$

The equations

$$(1) \quad \operatorname{ctnh} v = \frac{1}{\tanh v}, \quad \operatorname{sech} v = \frac{1}{\cosh v}, \quad \operatorname{csch} v = \frac{1}{\sinh v}$$

define, respectively, the *hyperbolic cotangent*, *hyperbolic secant*, and *hyperbolic cosecant*. The ratios used in (C) and (1) are the same as those in (2), p. 2, for the corresponding trigonometric functions.

The following relations hold:

$$(2) \quad 1 - \tanh^2 v = \operatorname{sech}^2 v, \quad \operatorname{ctnh}^2 v - 1 = \operatorname{csch}^2 v,$$

analogous to formulas in (2), p. 2. The proof of the first formula is given below.

The following statements hold for the values of the hyperbolic functions. They should be verified.

$\sinh v$ can have any value; $\cosh v$, any positive value not less than 1; $\operatorname{sech} v$, any positive value not exceeding 1; $\tanh v$, any value numerically less than 1; $\operatorname{ctnh} v$, any value numerically greater than 1; $\operatorname{csch} v$, any value except zero. Also, from the definitions, we have

$$(3) \quad \begin{aligned} \sinh(-v) &= -\sinh v, & \operatorname{csch}(-v) &= -\operatorname{csch} v, \\ \cosh(-v) &= \cosh v, & \operatorname{sech}(-v) &= \operatorname{sech} v, \\ \tanh(-v) &= -\tanh v, & \operatorname{ctnh}(-v) &= -\operatorname{ctnh} v. \end{aligned}$$

ILLUSTRATIVE EXAMPLE. Given $\tanh x = \frac{1}{2}$. Find the values of the other hyperbolic functions.

Solution. In (B) divide each term by $\cosh^2 x$. Then we get

$$1 - \frac{\sinh^2 x}{\cosh^2 x} = \frac{1}{\cosh^2 x}.$$

Therefore

$$1 - \tanh^2 x = \operatorname{sech}^2 x. \quad \text{By (C) and (1)}$$

Since $\tanh x = \frac{1}{2}$, this equation gives $\operatorname{sech} x = \frac{2}{3}$, the negative value being inadmissible. Then

$$\cosh x = \frac{1}{\operatorname{sech} x} = \frac{3}{2}, \quad \text{by (1)}$$

$$\sinh x = \cosh x \tanh x = \frac{3}{2} \cdot \frac{1}{2} = \frac{3}{4}, \quad \text{by (C)}$$

$$\operatorname{ctnh} x = \frac{2}{1}, \text{ and } \operatorname{csch} x = \frac{2}{3}. \quad \text{By (1)}$$

212. Table of values of the hyperbolic sine, cosine, and tangent.

Graphs. A table giving the values, to four significant figures, of $\sinh v$, $\cosh v$, $\tanh v$ for values of v from 0 to 5.9 is shown on p. 416. For negative values of v , use the relations (3), Art. 211.

HYPERBOLIC FUNCTIONS

v	$\sinh v$	$\cosh v$	$\tanh v$	v	$\sinh v$	$\cosh v$	$\tanh v$	v	$\sinh v$	$\cosh v$	$\tanh v$
00	0000	1.000	.0000	.50	.5211	1.128	.4621	1.0	1.175	1.543	.7616
01	0100	1.000	.0100	.51	.5324	1.133	.4700	1.1	1.336	1.669	.8005
02	0200	1.000	.0200	.52	.5438	1.138	.4777	1.2	1.509	1.811	.8337
03	.0300	1.000	.0300	.53	.5552	1.144	.4854	1.3	1.698	1.971	.8617
04	0400	1.001	.0400	.54	.5666	1.149	.4930	1.4	1.904	2.151	.8854
05	0500	1.001	.0500	.55	.5782	1.155	.5005	1.5	2.129	2.352	.9052
06	0600	1.002	.0599	.56	.5897	1.161	.5080	1.6	2.376	2.577	.9217
07	0701	1.002	.0699	.57	.6014	1.167	.5154	1.7	2.646	2.828	.9354
08	.0801	1.003	.0798	.58	.6131	1.173	.5227	1.8	2.942	3.107	.9468
09	.0901	1.004	.0898	.59	.6248	1.179	.5299	1.9	3.268	3.418	.9562
10	1002	1.005	.0997	.60	.6367	1.185	.5370	2.0	3.627	3.762	.9640
11	1102	1.006	.1096	.61	.6485	1.192	.5441	2.1	4.022	4.144	.9705
12	1203	1.007	.1194	.62	.6605	1.198	.5511	2.2	4.457	4.568	.9757
13	1304	1.008	.1293	.63	.6725	1.205	.5581	2.3	4.937	5.037	.9801
14	1405	1.010	.1391	.64	.6846	1.212	.5649	2.4	5.466	5.557	.9837
15	1506	1.011	.1489	.65	.6967	1.219	.5717	2.5	6.050	6.132	.9866
16	1607	1.013	.1587	.66	.7090	1.226	.5784	2.6	6.695	6.769	.9890
17	1708	1.014	.1684	.67	.7213	1.233	.5850	2.7	7.406	7.473	.9910
18	.1810	1.016	.1781	.68	.7336	1.240	.5915	2.8	8.192	8.253	.9926
19	.1911	1.018	.1878	.69	.7461	1.248	.5980	2.9	9.060	9.115	.9940
20	2013	1.020	.1974	.70	.7586	1.255	.6044	3.0	10.02	10.07	.9951
21	2115	1.022	.2070	.71	.7712	1.263	.6107	3.1	11.08	11.12	.9960
22	2218	1.024	.2165	.72	.7838	1.271	.6169	3.2	12.25	12.29	.9967
23	2320	1.027	.2260	.73	.7966	1.278	.6231	3.3	13.54	13.57	.9973
24	2423	1.029	.2355	.74	.8094	1.287	.6291	3.4	14.97	15.00	.9978
25	2526	1.031	.2449	.75	.8223	1.295	.6352	3.5	16.54	16.57	.9982
26	2629	1.034	.2543	.76	.8353	1.303	.6411	3.6	18.29	18.31	.9985
27	2733	1.037	.2636	.77	.8484	1.311	.6469	3.7	20.21	20.24	.9988
28	.2837	1.039	.2729	.78	.8615	1.320	.6527	3.8	22.34	22.36	.9990
29	2941	1.042	.2821	.79	.8748	1.329	.6584	3.9	24.69	24.71	.9992
30	3045	1.045	.2913	.80	.8881	1.337	.6640	4.0	27.29	27.31	.9993
31	3150	1.048	.3004	.81	.9015	1.346	.6696	4.1	30.16	30.18	.9995
32	3255	1.052	.3095	.82	.9150	1.355	.6751	4.2	33.31	33.35	.9996
33	3360	1.055	.3185	.83	.9286	1.365	.6805	4.3	36.84	36.86	.9996
34	3466	1.058	.3275	.84	.9423	1.374	.6858	4.4	40.72	40.73	.9997
35	3572	1.062	.3364	.85	.9561	1.384	.6911	4.5	45.00	45.01	.9998
36	3678	1.066	.3452	.86	.9700	1.393	.6963	4.6	49.74	49.75	.9998
37	3785	1.069	.3540	.87	.9840	1.403	.7014	4.7	54.97	54.98	.9998
38	3892	1.073	.3627	.88	.9981	1.413	.7064	4.8	60.75	60.76	.9999
39	4000	1.077	.3714	.89	1.012	1.423	.7114	4.9	67.14	67.15	.9999
40	4108	1.081	.3800	.90	1.027	1.433	.7163	5.0	74.20	74.21	.9999
41	4216	1.085	.3885	.91	1.041	1.443	.7211	5.1	82.01	82.01	.9999
42	.4325	1.090	.3969	.92	1.055	1.454	.7259	5.2	90.63	90.64	.9999
43	4434	1.094	.4053	.93	1.070	1.465	.7306	5.3	100.17	100.17	1.0000
44	.4543	1.098	.4136	.94	1.085	1.475	.7352	5.4	110.70	110.71	1.0000
45	.4653	1.103	.4219	.95	1.099	1.486	.7398	5.5	122.34	122.35	1.0000
46	.4764	1.108	.4301	.96	1.114	1.497	.7443	5.6	135.21	135.22	1.0000
47	.4875	1.112	.4382	.97	1.129	1.509	.7487	5.7	149.43	149.44	1.0000
48	.4986	1.117	.4462	.98	1.145	1.520	.7531	5.8	165.15	165.15	1.0000
49	.5098	1.122	.4542	.99	1.160	1.531	.7574	5.9	182.52	182.52	1.0000

When $r \rightarrow +\infty$, $\sinh r$ and $\cosh r$ become infinite, while $\tanh r$ approaches unity as a limit.

Graphs of $\sinh x$, $\cosh x$, and $\tanh x$ (Figs. 1, 2, 3) are easily drawn by making use of the table.

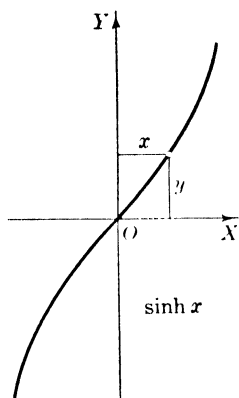


FIG. 1

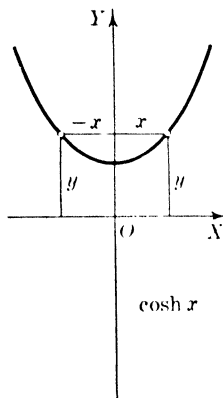


FIG. 2

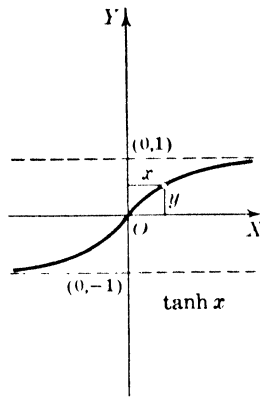


FIG. 3

213. Hyperbolic functions of $v + w$. Formulas for hyperbolic functions, corresponding to two of (4), p. 3, are

$$(D) \quad \sinh (v+w)=\sinh v \cosh w+\cosh v \sinh w,$$

$$(E) \quad \cosh (v+w)=\cosh v \cosh w+\sinh v \sinh w.$$

Proof of (D). From the definition (A), replacing v by $v+w$, we have

$$(1) \quad \sinh (v+w)=\frac{e^{v+w}-e^{-(v+w)}}{2},$$

$$(2) \quad \cosh (v+w)=\frac{e^{v+w}+e^{-(v+w)}}{2}.$$

The right-hand member of (1) is transformed as follows, making use of (1), Art. 210.

$$\begin{aligned} & \frac{e^{v+w}-e^{-(v+w)}}{2}=\frac{e^v e^w-e^{-v} e^{-w}}{2} \\ & =\frac{(\cosh v+\sinh v)(\cosh w+\sinh w)-(\cosh v-\sinh v)(\cosh w-\sinh w)}{2} . \end{aligned}$$

Multiplying out and reducing, we get (D). Formula (E) is proved in the same way.

If we set $w=v$ in (D) and (E), we have

$$(3) \quad \sinh 2 v=2 \sinh v \cosh v,$$

$$(4) \quad \cosh 2 v=\cosh ^2 v+\sinh ^2 v.$$

These are analogous to the formulas for $\sin 2x$ and $\cos 2x$, respectively, of (5), p. 3. From (B) and (4), we get results which correspond to the formulas for $\sin^2 x$ and $\cos^2 x$ in (5), p. 3. These are

$$(5) \quad \sinh^2 v = \frac{1}{2} \cosh 2v - \frac{1}{2}, \quad \cosh^2 v = \frac{1}{2} \cosh 2v + \frac{1}{2}.$$

Other relations for hyperbolic functions, which may be compared with those on page 3 for trigonometric functions, are given in the problems.

ILLUSTRATIVE EXAMPLE. Derive the formula

$$(6) \quad \tanh v = \frac{\sinh 2v}{\cosh 2v + 1}.$$

Solution. From (5), by division, we get

$$(7) \quad \tanh^2 v = \frac{\cosh 2v - 1}{\cosh 2v + 1}.$$

Now

$$\frac{\cosh 2v - 1}{\cosh 2v + 1} = \frac{\cosh 2v + 1}{\cosh 2v + 1} - \frac{\cosh^2 2v - 1}{(\cosh 2v + 1)^2}.$$

By (B), $\cosh^2 2v - 1 = \sinh^2 2v$. Hence (7) becomes

$$(8) \quad \tanh^2 v = \frac{\sinh^2 2v}{(\cosh 2v + 1)^2},$$

and therefore

$$\tanh v = \pm \frac{\sinh 2v}{\cosh 2v + 1}.$$

The sign before the right-hand member must now be examined. From (3) we have

$$\sinh 2v = \frac{2 \sinh v}{\cosh v} \cosh^2 v - 2 \tanh v \cosh^2 v.$$

Therefore $\sinh 2v$ and $\tanh v$ will always agree in sign. Also $\cosh 2v + 1$ is always positive. Hence the positive sign must be used, and we get (6).

If v is replaced by $\frac{1}{2}v$, (6) becomes

$$(9) \quad \tanh \frac{v}{2} = \frac{\sinh v}{\cosh v + 1}.$$

PROBLEMS

1. The value of one hyperbolic function is given. Find the values of the others and check as far as possible by the table on page 416.

(a) $\cosh x = 1.25$.

(c) $\sinh x = 10$.

(b) $\operatorname{csch} x = -0.75$.

(d) $\operatorname{ctnh} x = -2.5$.

Prove each of the formulas in Problems 2-7, and compare with the corresponding formula (if any) in (2), (4)-(6), pp. 2, 3.

2. $1 - \operatorname{ctnh}^2 v = -\operatorname{csch}^2 v$.

3. $\sinh (v - w) = \sinh v \cosh w - \cosh v \sinh w$,

$\cosh (v - w) = \cosh v \cosh w - \sinh v \sinh w$.

$$4. \tanh (r \pm w) = \frac{\tanh r \pm \tanh w}{1 \pm \tanh r \tanh w}.$$

$$5. \sinh \frac{r}{2} = \pm \sqrt{\frac{\cosh r - 1}{2}}, \quad \cosh \frac{r}{2} = + \sqrt{\frac{\cosh r + 1}{2}}.$$

$$6. \sinh r + \sinh w = 2 \sinh \frac{1}{2}(r + w) \cosh \frac{1}{2}(r - w), \\ \cosh r + \cosh w = 2 \cosh \frac{1}{2}(r + w) \cosh \frac{1}{2}(r - w).$$

$$7. \tanh \frac{1}{2}(r - w) = \frac{\sinh r - \sinh w}{\cosh r + \cosh w}.$$

8. Show that the equation of the catenary (figure, p. 532) may be written $y = a \cosh \frac{x}{a}$.

9. Solve the differential equation $\frac{d^2y}{dx^2} - y = 0$ in terms of hyperbolic functions, given that $y = 3$ when $x = 0$, and $y = 0$ when $\tanh x = \frac{1}{3}$.

Ans. $y = 3 \cosh x - 3.75 \sinh x$.

10. Show that $\operatorname{sech}(-x) = \operatorname{sech} x$. Draw the graph and prove $\lim_{x \rightarrow \infty} \operatorname{sech} x = 0$.

11. Show that $\operatorname{ctnh}(-x) = -\operatorname{ctnh} x$. Draw the graph and prove $\lim_{x \rightarrow +\infty} \operatorname{ctnh} x = 1$.

12. Show that $\operatorname{csch}(-x) = -\operatorname{csch} x$. Draw the graph and prove $\lim_{x \rightarrow \infty} \operatorname{csch} x = 0$.

$$13. \text{ Prove } \quad (a) \sinh 3u = 3 \sinh u + 4 \sinh^3 u; \\ (b) \cosh 3u = 4 \cosh^3 u - 3 \cosh u.$$

14. Show that $(\sinh x + \cosh x)^n = \sinh nx + \cosh nx$. (n any positive integer.)

$$15. \text{ Prove that } \sinh^2 x - \sinh^2 y = \sinh(x + y) \sinh(x - y).$$

$$16. \text{ Simplify } \frac{\cosh 2u + \cosh 4v}{\sinh 2u + \sinh 4v}. \quad \text{Ans. } \operatorname{ctnh}(u + 2v).$$

17. Parametric equations for the *tractrix* may be written

$$x = t - a \tanh \frac{t}{a}, \quad y = a \operatorname{sech} \frac{t}{a}.$$

The parameter is t , and a is a constant. Plot the curve when $a = 4$. (The tractrix is the curve for which the length of the tangent (Art. 43) is constant and equal to a . Figure in Chapter XXVI.)

$$18. \text{ Solve } \frac{d^2y}{dx^2} = n^2(y - mx^2).$$

$$\text{Ans. } y = A \cosh nx + B \sinh nx + mx^2 + \frac{2m}{n^2}.$$

214. Derivatives. The formulas, in which v is a function of x , are as follows.

$$\text{XXVII} \quad \frac{d}{dx} \sinh v = \cosh v \frac{dv}{dx}.$$

$$\text{XXVIII} \quad \frac{d}{dx} \cosh v = \sinh v \frac{dv}{dx}.$$

$$\text{XXIX} \quad \frac{d}{dx} \tanh v = \operatorname{sech}^2 v \frac{dv}{dx}.$$

$$\text{XXX} \quad \frac{d}{dx} \operatorname{ctnh} v = -\operatorname{csch}^2 v \frac{dv}{dx}.$$

$$\text{XXXI} \quad \frac{d}{dx} \operatorname{sech} v = -\operatorname{sech} v \tanh v \frac{dv}{dx}.$$

$$\text{XXXII} \quad \frac{d}{dx} \operatorname{csch} v = -\operatorname{csch} v \operatorname{ctnh} v \frac{dv}{dx}.$$

Proof of XXVII. By (A), $\sinh v = \frac{e^v - e^{-v}}{2}$.

$$\begin{aligned} \text{Then} \quad \frac{d}{dx} \sinh v &= \frac{e^v \frac{dv}{dx} + e^{-v} \frac{dv}{dx}}{2} \\ &= \frac{e^v + e^{-v}}{2} \frac{dv}{dx} \\ &= \cosh v \frac{dv}{dx}, \end{aligned}$$

using (A).

Formula XXVIII is proved in a similar manner. The proof of XXIX is analogous to that given in Art. 72 for the derivative of $\tan v$. To prove XXX XXXII, differentiate the forms as given in (1), Art. 211. The details are left as exercises.

215. Relations to the equilateral hyperbola. The curve for which

$$(1) \quad x = a \cosh v, \quad y = a \sinh v$$

are parametric equations is the equilateral hyperbola $x^2 - y^2 = a^2$. For, eliminating the parameter v by squaring and subtracting, we have

$$x^2 - y^2 = a^2(\cosh^2 v - \sinh^2 v) = a^2. \quad \text{By (B)}$$

Fig. 2, p. 421, shows a hyperbolic sector OAP_1 bounded by the arc AP_1 of (1), the semitransverse axis OA , and the radius vector OP_1 . At P_1 , $v = v_1$.

Theorem. *The area of the hyperbolic sector OAP_1 equals $\frac{1}{2} a^2 v_1$.*

Proof. Let (ρ, θ) be the polar coordinates of any point on the arc AP_1 . Then the element of area is (Art. 159) $dA = \frac{1}{2} \rho^2 d\theta$.

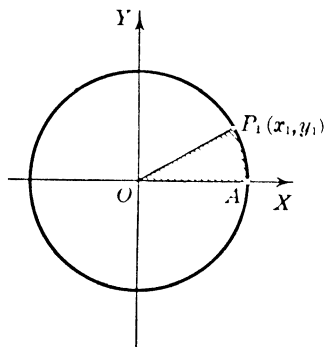


FIG. 1

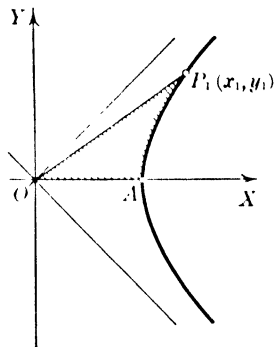


FIG. 2

But $\rho^2 = x^2 + y^2 = a^2(\cosh^2 v + \sinh^2 v)$. Using (1)

Also by (5), p. 4,

$$\theta = \arctan \frac{y}{x} = \arctan (\tanh v). \quad \text{By (1)}$$

Therefore
$$\frac{d\theta}{dv} = \frac{\operatorname{sech}^2 v}{1 + \tanh^2 v}.$$

By XXII, p. 87, and XXIX

Using (C) and (1), Art. 211, we get

$$d\theta = \frac{dv}{\cosh^2 v + \sinh^2 v},$$

and therefore

$$dA = \frac{1}{2} a^2 dv.$$

The theorem follows by integration, since $v = 0$ at A .

Q.E.D.

The parametric equations of the circle in Fig. 1 are

$$x = r \cos t, \quad y = r \sin t. \quad \text{Art. 81}$$

The parameter t equals t_1 at P_1 , and t_1 is the measure of the central angle AOP_1 in radians. Hence the area of the circular sector AOP_1 is $\frac{1}{2} r^2 t_1$.

Let $r = a = 1$. Then in Fig. 1, for $P(x, y)$,

$$x = \cos t, \quad y = \sin t, \quad \frac{1}{2} t = \text{area } AOP.$$

In Fig. 2, for $P(x, y)$,

$$x = \cosh v, \quad y = \sinh v, \quad \frac{1}{2} v = \text{area } AOP.$$

Hyperbolic functions, therefore, have the same relations to the equilateral hyperbola as the trigonometric functions do to the circle.

PROBLEMS

1. Show that the element of length of arc for the catenary $y = a \cosh \frac{x}{a}$ is given by $ds = \cosh \frac{x}{a} dx$.

2. In the catenary of Problem 1 prove that the radius of curvature equals $\frac{y^2}{a}$.

Verify the following expansions of functions by Maclaurin's series, and determine for what values of the variable they are convergent.

$$3. \sinh x = x + \frac{x^3}{3} + \frac{x^5}{5} + \cdots + \frac{x^{2n-1}}{2n-1} + \cdots. \quad \text{Ans. All values}$$

$$4. \cosh x = 1 + \frac{x^2}{2} + \frac{x^4}{4} + \cdots + \frac{x^{2n}}{2n} + \cdots. \quad \text{Ans. All values.}$$

Verify the following expansions, using the series in Problems 3 and 4 and the methods explained in Art. 195.

$$5. \operatorname{sech} x = 1 - \frac{1}{2}x^2 + \frac{5}{24}x^4 - \frac{61}{720}x^6 + \cdots.$$

$$6. \tanh x = x - \frac{1}{3}x^3 + \frac{2}{15}x^5 - \frac{17}{315}x^7 + \cdots.$$

7. Test the function $5 \cosh x + 4 \sinh x$ for maximum or minimum values. Ans. Minimum value, 3.

8. Test the function $A \sinh x + B \cosh x$ for maximum or minimum values. Ans. If $B^2 > A^2$, a maximum value $= \sqrt{B^2 - A^2}$ if $B < 0$; a minimum value $= \sqrt{B^2 - A^2}$ if $B > 0$.

9. Derive the series in Problems 3 and 4 from the series for e^x and e^{-x} by subtraction and addition. (Use (A) and Art. 195.)

10. Let ds = length of the element of arc; let $\rho = \sqrt{x^2 + y^2}$ = radius vector of $P(x, y)$ for the circle or equilateral hyperbola of Art. 215, and take limits of integration for the arc AP_1 in Figs. 1 and 2, p. 421. Prove

$$(a) \int \frac{ds}{\rho} = t_1 \text{ for the circle; } (b) \int \frac{ds}{\rho} = r_1 \text{ for the hyperbola.}$$

$$11. \text{ Prove } \lim_{x \rightarrow +\infty} (\cosh x - \sinh x) = 0.$$

12. Evaluate each of the following indeterminate forms.

$$(a) \lim_{x \rightarrow 0} \frac{\sinh x}{x}. \quad (b) \lim_{x \rightarrow 0} \frac{\tanh x}{x}.$$

$$(c) \lim_{x \rightarrow 0} \frac{1 - \cosh x}{x^2}. \quad \text{Ans. } -\frac{1}{2}.$$

13. Given $\tan \phi = \sinh x$. Prove $\frac{d\phi}{dx} = \operatorname{sech} x$.

14. Derive the expansion

$$\operatorname{arc tan} (\sinh x) = x - \frac{1}{6} x^3 + \frac{1}{24} x^5 - \frac{61}{30240} x^7 + \dots$$

by integration as in Art. 196, using the result in Problem 5.

15. Prove the following theorems for the tractrix (see figure)

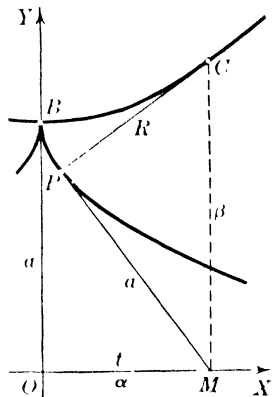
$$x = t - a \tanh \frac{t}{a}, \quad y = a \operatorname{sech} \frac{t}{a}.$$

(a) The parameter t equals the intercept of the tangent on the x -axis.

(b) The constant a equals the length of the tangent (Art. 43).

(c) The evolute is the catenary $\beta = a \cosh \frac{\alpha}{a}$.

(d) The radius of curvature PC is $a \sinh \frac{t}{a}$.



216. Inverse hyperbolic functions. The relation

$$(1) \quad y = \sinh v$$

is also written

$$(2) \quad v = \sinh^{-1} y,$$

and read " v equals the inverse hyperbolic sine of y ." Therefore $\sinh v$ and $\sinh^{-1} y$ are inverse functions (Art. 39). The same notation and nomenclature are used for the other inverse hyperbolic functions, $\cosh^{-1} v$ ("inverse hyperbolic cosine of v "), etc.

The curves

$$(3) \quad y = \sinh x, \quad y = \cosh x, \quad y = \tanh x$$

are shown again on page 424. Assume now that y is given.

In Fig. 1, y may have any value, positive or negative, and then the value of x is uniquely determined.

In Fig. 2, y may have any positive value not less than 1. When $y > 1$, x has two values equal numerically and differing in sign.

In Fig. 3, y may have any value numerically less than 1, and then the value of x is uniquely determined.

Summarized, the results are

The function $\sinh^{-1} v$ is uniquely determined for any value of v . Also $\sinh^{-1}(-v) = -\sinh^{-1} v$.

The function $\cosh^{-1} v$, when $v > 1$, has two values differing only in sign. Also $\cosh^{-1} 1 = 0$.

The function $\tanh^{-1} v$ is uniquely determined when $v^2 < 1$. Also $\tanh^{-1}(-v) = -\tanh^{-1} v$.

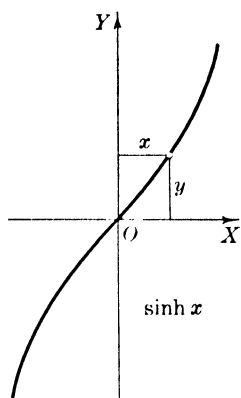


FIG. 1

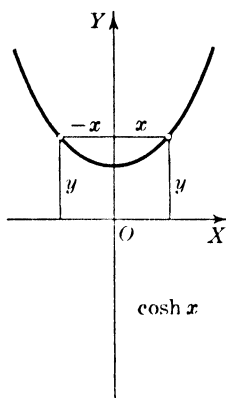


FIG. 2

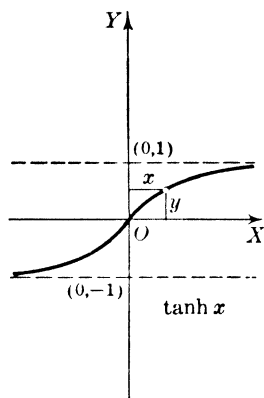


FIG. 3

Hyperbolic functions were defined in Art. 210 in terms of exponential functions. The inverse hyperbolic functions are expressible in terms of logarithmic functions. The relations are

$$(F) \quad \sinh^{-1} x = \ln(x + \sqrt{x^2 + 1}). \quad (\text{Any } x)$$

$$(G) \quad \cosh^{-1} x = \ln(x \pm \sqrt{x^2 - 1}). \quad (x \geq 1)$$

$$(H) \quad \tanh^{-1} x = \frac{1}{2} \ln \frac{1+x}{1-x}. \quad (x^2 < 1)$$

Proof of (F). Let $v = \sinh^{-1} x$. Then

$$(4) \quad x = \sinh v = \frac{e^v - e^{-v}}{2}. \quad \text{By (A)}$$

To solve (4) for v , write it as follows:

$$e^v - \frac{1}{e^v} - 2x = 0, \quad \text{or} \quad e^{2v} - 2xe^v - 1 = 0.$$

This is a quadratic equation in e^v . Solving, $e^v = x \pm \sqrt{x^2 + 1}$.

Since e^v is always positive, the negative sign before the radical must be discarded. Hence, using Napierian logarithms, we have (F).

Proof of (G). Let $v = \cosh^{-1} x$. Then

$$(5) \quad x = \cosh v = \frac{e^v + e^{-v}}{2}. \quad \text{By (A)}$$

Clearing and reducing, we have $e^{2v} - 2xe^v + 1 = 0$.

Solving, $e^v = x \pm \sqrt{x^2 - 1}$.

Both values must be retained. Taking logarithms gives (G).

Proof of (H). Let $v = \tanh^{-1} x$. Then

$$(6) \quad x = \tanh v = \frac{e^v - e^{-v}}{e^v + e^{-v}}. \quad \text{By (C)}$$

Clearing of fractions and simplifying, the result is

$$(x-1)e^v + (x+1)e^{-v} = 0. \text{ Hence } e^{2v} = \frac{1+x}{1-x}.$$

Taking logarithms, we have (H).

ILLUSTRATIVE EXAMPLE. Transform

$$(7) \quad 5 \cosh x + 4 \sinh x$$

into the form $C \cosh (x+a)$, where C and a are constants, and find C and a .

Solution. By (E), Art. 213, we have

$$(8) \quad C \cosh (x+a) = C \cosh x \cosh a + C \sinh x \sinh a.$$

Hence (7) will have the desired form if C and a satisfy the equations

$$(9) \quad C \cosh a = 5, \quad C \sinh a = 4.$$

Squaring, subtracting, and using (B), Art. 210, we get $C^2 = 9$. Then $C = \pm 3$, since $\cosh a$ must be positive. Also, by division, $\tanh a = \frac{4}{5}$. Hence

$$a = \tanh^{-1} 0.8 = \frac{1}{2} \ln 9. \quad \text{By (H)}$$

Therefore $a = 1.099$ and

$$(10) \quad 5 \cosh x + 4 \sinh x = 3 \cosh (x + 1.099).$$

The graph of the function $5 \cosh x + 4 \sinh x$ may be obtained from the graph of $5 \cosh x$ by translating the y -axis to the new origin (1.099, 0). (Compare with Illustrative Example 2, p. 391.)

When x is given, the values of $\sinh^{-1} x$, $\cosh^{-1} x$, or $\tanh^{-1} x$ can be determined by the table on page 416 to not more than three significant figures. For example, $\sinh^{-1} 0.25 = 0.247$; $\cosh^{-1} 3 = \pm 1.76$. For greater accuracy (F), (G), or (H) may be used if tables of Napierian logarithms are at hand.*

217. Derivatives (continued). The formulas, in which v is a function of x , are as follows.

$$\text{XXXIII} \quad \frac{d}{dx} \sinh^{-1} v = \frac{\frac{dv}{dx}}{\sqrt{v^2 + 1}}. \quad (\text{Any } v)$$

$$\text{XXXIV} \quad \frac{d}{dx} \cosh^{-1} v = \frac{\frac{dv}{dx}}{\pm \sqrt{v^2 - 1}}. \quad (v > 1)$$

$$\text{XXXV} \quad \frac{d}{dx} \tanh^{-1} v = \frac{\frac{dv}{dx}}{1 - v^2}. \quad (v^2 < 1)$$

* The Smithsonian Mathematical Tables, "Hyperbolic Functions" (1909), give the values of $\sinh u$, $\cosh u$, $\tanh u$, $\coth u$ to five significant figures. Values of the corresponding inverse functions to five significant figures may be found from these tables.

Proof of XXXIII. (Compare Art. 75.) Let

$$y = \sinh^{-1} v;$$

then

$$v = \sinh y.$$

Differentiating with respect to y , by XXVII,

$$\frac{dv}{dy} = \cosh y;$$

therefore

$$\frac{dy}{dv} = \frac{1}{\cosh y}. \quad \text{By (C), Art. 39}$$

Since v is a function of x , this may be substituted in (A), Art. 38, giving

$$\frac{dy}{dx} = \frac{1}{\cosh y} \frac{dv}{dx} = \frac{1}{\sqrt{v^2 + 1}} \frac{dv}{dx}.$$

[$\cosh y = \sqrt{\sinh^2 y + 1} = \sqrt{v^2 + 1}$, by (B)]

The proofs of XXXIV and XXXV are similar. Other formulas are the following.

$$(I) \quad \operatorname{ctnh}^{-1} x = \frac{1}{2} \ln \frac{x+1}{x-1}. \quad (x^2 > 1)$$

$$(J) \quad \operatorname{sech}^{-1} x = \ln \left(\frac{1}{x} \pm \sqrt{\frac{1}{x^2} - 1} \right). \quad (0 < x \leq 1)$$

$$(K) \quad \operatorname{csch}^{-1} x = \ln \left(\frac{1}{x} + \sqrt{\frac{1}{x^2} + 1} \right). \quad (x^2 > 0)$$

$$\text{XXXVI} \quad \frac{d}{dx} \operatorname{ctnh}^{-1} v = \frac{-\frac{dv}{dx}}{v^2 - 1}. \quad (v^2 > 1)$$

$$\text{XXXVII} \quad \frac{d}{dx} \operatorname{sech}^{-1} v = \frac{-\frac{dv}{dx}}{\pm v \sqrt{1 - v^2}}. \quad (0 < v < 1)$$

$$\text{XXXVIII} \quad \frac{d}{dx} \operatorname{csch}^{-1} v = \frac{-\frac{dv}{dx}}{v^2 \sqrt{1 + \frac{1}{v^2}}}. \quad (v^2 > 0)$$

Details of the proofs are called for in Problems 5-8 on the next page.

PROBLEMS

1. Show that the two values of $\cosh^{-1} x$ in (G) differ only in sign.
2. Draw the graph of $y = \frac{1}{2} \sinh^{-1} x$. Check in the figure the values of y and y' when $x = 2$. *Ans.* $y = 0.72$, $y' = 0.2236$.
3. Prove XXXIII directly by differentiating (F).
4. Draw the graph of each of the following and check in the figure the values of y and y' for the given value of x .
 - (a) $y = \cosh^{-1} x$; $x = 2$.
 - (b) $y = \tanh^{-1} x$; $x = -0.75$.
5. Prove XXXIV and XXXV.
6. Derive (I) and XXXVI.
7. Derive (J) and XXXVII.
8. Derive (K) and XXXVIII.
9. Derive the expansion

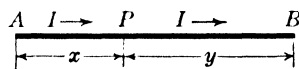
$$\tanh^{-1} x = x + \frac{x^3}{3} + \frac{x^5}{5} + \cdots$$

by Art. 195.

10. Given $\sinh x = \tan \phi$. Prove
 - (a) $x = \ln (\sec \phi + \tan \phi)$; (b) $\frac{dx}{d\phi} = \sec \phi$.
11. Show that $\operatorname{csch}^{-1} v = \sinh^{-1} \frac{1}{v}$. Derive XXXVIII from XXXIII, using this relation.
12. Evaluate $\lim_{x \rightarrow \infty} x \operatorname{etnh}^{-1} x$. *Ans.* 1.
13. Evaluate $\lim_{x \rightarrow \infty} x \operatorname{csch}^{-1} x$.
14. Derive the expansion

$$\sinh^{-1} x = x - \frac{1}{6} x^3 + \frac{1 \cdot 3}{2 \cdot 4 \cdot 5} x^5 - \cdots.$$
15. Evaluate $\lim_{x \rightarrow +\infty} (\sinh^{-1} x - \ln x)$. *Ans.* $\ln 2$.
16. Show that $\operatorname{etnh}^{-1} v = \tanh^{-1} \frac{1}{v}$, $\operatorname{sech}^{-1} v = \cosh^{-1} \frac{1}{v}$, and verify XXXVI and XXXVII from these relations.
17. Prove $\frac{d}{dx} \tanh^{-1} \frac{\tanh a \tan x}{\operatorname{sech} a + \sec x} = \frac{\sinh a}{1 + \cosh a \cos x}$.
18. Draw the graphs of (a) $y = \operatorname{etnh}^{-1} x$; (b) $y = \operatorname{sech}^{-1} x$; (c) $y = \operatorname{csch}^{-1} x$, using the theorem of Problem 28, p. 41.

218. Telegraph line. Assume in a telegraph line that a "steady state" of flow of electricity from A , the home end, to B , the receiving end, has been established, with perfect insulation and uniform linear leakage. P is any intermediate point. We need to consider:



the *electromotive force* (volts), e.m.f., E_A at A , E_B at B , E at P ;
the *current strength* (amperes), I_A at A , I_B at B , I at P ;
the *characteristic constants* α and r_0 , whose values depend upon the linear resistance and leakage. They are positive numbers.

Let $x = AP$. Then it is shown in books on electrical engineering that E and I are functions of x such that

$$(1) \quad \frac{d^2 E}{dx^2} - \alpha^2 E = 0,$$

$$(2) \quad r_0 \alpha I = -\frac{dE}{dx}.$$

We wish to find the e.m.f. and current strength at P . They are

$$(3) \quad E = E_A \cosh \alpha x - r_0 I_A \sinh \alpha x,$$

$$(4) \quad I = I_A \cosh \alpha x - \frac{E_A}{r_0} \sinh \alpha x.$$

Proof. The complete solution of (1) is (Illustrative Example, Art. 210)

$$(5) \quad E = A \cosh \alpha x + B \sinh \alpha x.$$

Substituting in (2), the result is

$$(6) \quad r_0 I = -A \sinh \alpha x - B \cosh \alpha x.$$

But $E = E_A$, $I = I_A$ when $x = 0$. Therefore $A = E_A$, $B = -r_0 I_A$, and (5) and (6) become (3) and (4) respectively.

For the solution in terms of the e.m.f. and current strength at the receiving end, see Problem 2 below.

PROBLEMS

All refer to a telegraph line in a "steady state," and $L = AB$.

1. Given $E_A = 200$ volts, $L = 500$ kilometers, $r_0 = 4000$ ohms, $\alpha = 0.0025$, $I_B = 0$. Find I_A and E_B .

Ans. $I_A = 0.05 \tanh 1.25 = 0.04238$ ampere;

$E_B = 200 \operatorname{sech} 1.25 = 105.8$ volts $= 0.53 E_A$.

2. If $y = PB =$ distance of P from the receiving end, show that

$$E = E_B \cosh \alpha y + r_0 I_B \sinh \alpha y, \quad I = I_B \cosh \alpha y + \frac{E_B}{r_0} \sinh \alpha y.$$

3. Given $E_A = 200$ volts, $I_A = 0.04$ ampere, $r_0 = 4000$ ohms, $\alpha = 0.0025$. Show that

$$E = 120 \cosh (1.099 - 0.0025 x), \quad I = 0.03 \sinh (1.099 - 0.0025 x).$$

(See the Illustrative Example, Art. 216. Thus E tends towards a minimum value of 120 volts and I approaches 0 as x approaches 439.6.)

4. Given $E_A = 160$ volts, $I_A = 0.05$ ampere, $r_0 = 4000$ ohms, $\alpha = 0.0025$. Show that

$$E = 120 \sinh (1.099 - 0.0025 x), \quad I = 0.03 \cosh (1.099 - 0.0025 x).$$

(See the Illustrative Example, Art. 216. Thus E approaches zero and I decreases to a minimum value of 0.03 ampere when x approaches 439.6.)

5. Prove that $\frac{d^2 I}{dx^2} - \alpha^2 I = 0$. (Thus E and I are solutions of the same linear differential equation, which has the form $y'' - \alpha^2 y = 0$.)

6. Given $E_A = r_0 I_A$. Prove

- (a) $E = E_A e^{-\alpha x}$, $I = I_A e^{-\alpha x}$;
- (b) $E = r_0 I$;
- (c) $E \rightarrow 0$ when x becomes infinite.

(For example, if $r_0 = 4000$, and the impressed e.m.f. at the home end of the line is 4000 times the current strength, then at *every point* of the line the e.m.f. is 4000 times the current strength and diminishes towards zero as the length of the line is indefinitely increased.)

7. In Problem 6 show that the decrease in E at P at unit distance along the line from P equals $Ee^{-\alpha}$, where e is the Napierian base.

8. Prove the following.

- (a) If $I_B = 0$, then $E_A = r_0 I_A \coth \alpha L$.
- (b) If $E_B = 0$, then $E_A = r_0 I_A \tanh \alpha L$.

ADDITIONAL PROBLEMS

Derive the following relations.

1. If $E_A > r_0 I_A$ and $\tau = \tanh^{-1} \frac{r_0 I_A}{E_A}$, then

$$E = E_A \operatorname{sech} \tau \cosh (\tau - \alpha x), \quad I = I_A \operatorname{csch} \tau \sinh (\tau - \alpha x).$$

2. If $E_A < r_0 I_A$ and $\tau = \tanh^{-1} \frac{E_A}{r_0 I_A}$, then

$$E = E_A \operatorname{csch} \tau \sinh (\tau - \alpha x), \quad I = I_A \operatorname{sech} \tau \cosh (\tau - \alpha x).$$

219. Integrals. A list of elementary integrals involving hyperbolic functions and supplementing Art. 128 is given here.

$$(24) \quad \int \sinh v \, dv = \cosh v + C.$$

$$(25) \quad \int \cosh v \, dv = \sinh v + C.$$

$$(26) \quad \int \tanh v \, dv = \ln \cosh v + C.$$

$$(27) \quad \int \operatorname{ctnh} v \, dv = \ln \sinh v + C.$$

$$(28) \quad \int \operatorname{sech}^2 v \, dv = \tanh v + C.$$

$$(29) \quad \int \operatorname{csch}^2 v \, dv = -\operatorname{ctnh} v + C.$$

$$(30) \quad \int \operatorname{sech} v \tanh v \, dv = -\operatorname{sech} v + C.$$

$$(31) \quad \int \operatorname{csch} v \operatorname{ctnh} v \, dv = -\operatorname{csch} v + C.$$

The proofs follow immediately from **XXVII-XXXII**, except for (26) and (27). To prove (26), we have

$$\begin{aligned} \int \tanh v \, dv &= \int \frac{\sinh v}{\cosh v} \, dv && \text{by (C)} \\ &= \int \frac{d(\cosh v)}{\cosh v} = \ln \cosh v + C. \end{aligned}$$

The proof of (27) is similar.

ILLUSTRATIVE EXAMPLE. Derive the formulas

$$(1) \quad \int \operatorname{sech} v \, dv = \operatorname{arc tan} (\sinh v) + C;$$

$$(2) \quad \int \operatorname{csch} v \, dv = \ln \tanh \frac{v}{2} + C.$$

Solution. Since $\operatorname{sech} v = \frac{1}{\cosh v} = \frac{\cosh v}{\cosh^2 v} = \frac{\cosh v}{1 + \sinh^2 v}$, by (B)

we have
$$\begin{aligned} \int \operatorname{sech} v \, dv &= \int \frac{\cosh v \, dv}{1 + \sinh^2 v} = \int \frac{d(\sinh v)}{1 + \sinh^2 v} \\ &= \int d[\operatorname{arc tan} (\sinh v)] = \operatorname{arc tan} (\sinh v) + C. \end{aligned}$$

To derive (2) we have (compare Art. 131)

$$\begin{aligned}\operatorname{csch} r &= \operatorname{csch} r \frac{\operatorname{csch} r + \operatorname{ctnh} r}{\operatorname{csch} r + \operatorname{ctnh} r} \\ &= \frac{\operatorname{csch}^2 r + \operatorname{csch} r \operatorname{ctnh} r}{\operatorname{ctnh} r + \operatorname{csch} r}.\end{aligned}$$

$$\begin{aligned}\int \operatorname{csch} r \, dr &= - \int \frac{-\operatorname{csch}^2 r - \operatorname{csch} r \operatorname{ctnh} r}{\operatorname{ctnh} r + \operatorname{csch} r} \, dr \\ &= - \int \frac{d(\operatorname{ctnh} r + \operatorname{csch} r)}{\operatorname{ctnh} r + \operatorname{csch} r} \\ &= - \ln (\operatorname{ctnh} r + \operatorname{csch} r) + C \\ &= - \ln \left(\frac{\cosh r}{\sinh r} + \frac{1}{\sinh r} \right) + C && \text{by (1), Art. 211} \\ &= - \ln (\cosh r + 1) + \ln \sinh r + C = \ln \frac{\sinh r}{\cosh r + 1} + C \\ &= \ln \tanh \frac{r}{2} + C. && \text{By (9), Art. 213}\end{aligned}$$

PROBLEMS

Work out the following integrals.

1. $\int \sinh^2 r \, dr = \frac{1}{4} \sinh 2r - \frac{1}{2} r + C.$
2. $\int \cosh^2 r \, dr = \frac{1}{4} \sinh 2r + \frac{1}{2} r + C.$
3. $\int \tanh^2 r \, dr = r - \tanh r + C.$
4. $\int \operatorname{ctnh}^2 r \, dr = r - \operatorname{ctnh} r + C.$
5. $\int \sinh^3 r \, dr = \frac{1}{3} \cosh^3 r - \cosh r + C.$
6. $\int \cosh^3 r \, dr = \frac{1}{3} \sinh^3 r + \sinh r + C.$
7. $\int \tanh^3 r \, dr = \ln \cosh r - \frac{1}{2} \tanh^2 r + C.$
8. $\int \tanh^4 r \, dr = r - \tanh r - \frac{1}{3} \tanh^3 r + C.$
9. $\int \operatorname{csch}^3 r \, dr = -\frac{1}{2} \operatorname{csch} r \operatorname{ctnh} r - \frac{1}{2} \ln \tanh \frac{r}{2} + C.$
10. $\int x \sinh x \, dx = x \cosh x - \sinh x + C.$
11. $\int \cos x \sinh x \, dx = \frac{1}{2} (\cos x \cosh x + \sin x \sinh x) + C.$
12. $\int \sinh (mx) \sinh (nx) \, dx = \frac{1}{m^2 - n^2} [m \sinh (nx) \cosh (mx) - n \cosh (nx) \sinh (mx)] + C.$

Work out each of the following integrals.

$$13. \int \sinh^4 x \, dx.$$

$$15. \int \sin x \cosh x \, dx.$$

$$14. \int \operatorname{sech}^4 2x \, dx.$$

$$16. \int x \tanh x \, dx.$$

$$17. \int x^2 \cosh x \, dx.$$

$$18. \int e^x \sinh x \, dx.$$

$$19. \int e^{ax} \cosh x \, dx.$$

Work out each of the following, using the hyperbolic substitution indicated. (Compare Art. 135.)

$$20. \int \sqrt{x^2 - 4} \, dx; \quad x = 2 \cosh v. \quad \text{Ans. } \frac{1}{2} x \sqrt{x^2 - 4} - 2 \cosh^{-1} \frac{1}{2} x + C.$$

$$21. \int \frac{du}{(a^2 - u^2)^{\frac{3}{2}}}; \quad u = a \tanh z.$$

$$22. \int \frac{(x+2)dx}{x^2 + 2x + 5}; \quad x = 2 \sinh z - 1.$$

23. The arc of the catenary $y = a \cosh \frac{x}{a}$ from $(0, a)$ to (x, y) is revolved about the y -axis. Find the area of the curved surface generated, using hyperbolic functions.

24. Find the centroid of the hyperbolic sector OAP_1 in Fig. 2, Art. 215. (Compare Problem 12, p. 337.) $\text{Ans. } \bar{x} = \frac{2}{3} a \frac{\sinh v_1}{v_1}, \bar{y} = \frac{2}{3} a \frac{\cosh v_1 - 1}{v_1}.$

220. Integrals (continued). From XXXIII XXXVIII we may derive integrals. Some of them we have already met in Art. 128. Their values are now expressible in terms of inverse hyperbolic functions.

$$(32) \quad \int \frac{dv}{\sqrt{v^2 + a^2}} = \sinh^{-1} \frac{v}{a} + C. \quad (v \text{ any value})$$

$$(33) \quad \int \frac{dv}{\sqrt{v^2 - a^2}} = \cosh^{-1} \frac{v}{a} + C. \quad (v \geq a)$$

$$(34) \quad \int \frac{dv}{a^2 - v^2} = \frac{1}{a} \tanh^{-1} \frac{v}{a} + C. \quad (v^2 < a^2)$$

$$(35) \quad \int \frac{dv}{v^2 - a^2} = -\frac{1}{a} \operatorname{ctnh}^{-1} \frac{v}{a} + C. \quad (v^2 > a^2)$$

$$(36) \quad \int \frac{dv}{v\sqrt{a^2 - v^2}} = -\frac{1}{a} \operatorname{sech}^{-1} \frac{v}{a} + C. \quad (0 < v < a)$$

$$(37) \quad \int \frac{dv}{v\sqrt{v^2 + a^2}} = -\frac{1}{a} \operatorname{csch}^{-1} \frac{v}{a} + C. \quad (v \text{ any value})$$

$$(38) \quad \int \sqrt{v^2 + a^2} \, dv = \frac{v}{2} \sqrt{v^2 + a^2} + \frac{a^2}{2} \sinh^{-1} \frac{v}{a} + C.$$

$$(39) \quad \int \sqrt{v^2 - a^2} \, dv = \frac{v}{2} \sqrt{v^2 - a^2} - \frac{a^2}{2} \cosh^{-1} \frac{v}{a} + C.$$

In (33) and (39) the positive value of the inverse hyperbolic cosine must be used, and in (36) the positive value of the inverse hyperbolic secant.

Proofs of (32) and (33). Let $x = \frac{v}{a}$ in (F). Then

$$\sinh^{-1} \frac{v}{a} = \ln \left(\frac{v}{a} + \sqrt{\frac{v^2}{a^2} + 1} \right) = \ln (v + \sqrt{v^2 + a^2}) - \ln a.$$

Hence

$$(1) \quad \ln (v + \sqrt{v^2 + a^2}) = \sinh^{-1} \frac{v}{a} + \ln a.$$

In the same way, from (G) we get

$$(2) \quad \ln (v + \sqrt{v^2 - a^2}) = \cosh^{-1} \frac{v}{a} + \ln a.$$

Using these results in the right-hand member of (21), p. 193, we get (32) and (33).

Proofs of (34) and (35). Let $x = \frac{v}{a}$ in (H). Then

$$(3) \quad \frac{1}{2} \ln \frac{a+v}{a-v} = \tanh^{-1} \frac{v}{a}.$$

Then (34) follows from (3) and (19 a), p. 192.

In the same way, from (I) and (19), p. 192, we get (35).

$$\left[\ln (19), \ln \frac{v-a}{v+a} = -\ln \frac{v+a}{v-a} \right]$$

Proof of (36). Since

$$d\left(-\frac{1}{a} \operatorname{sech}^{-1} \frac{v}{a}\right) = \frac{\frac{1}{a} d\left(\frac{v}{a}\right)}{\pm \frac{v}{a} \sqrt{1 - \frac{v^2}{a^2}}} = \frac{dv}{\pm v \sqrt{a^2 - v^2}}, \quad \text{by XXXVII}$$

we have $\int \frac{dv}{v \sqrt{a^2 - v^2}} = -\frac{1}{a} \operatorname{sech}^{-1} \frac{v}{a}$ if the positive sign before the radical is chosen. The proof of (37) is similar.

Formulas (38) and (39) follow from (23), p. 193, using (1) and (2).

REMARK. Since

$$\operatorname{ctnh}^{-1} \frac{v}{a} = \tanh^{-1} \frac{a}{v}, \quad \operatorname{sech}^{-1} \frac{v}{a} = \cosh^{-1} \frac{a}{v}, \quad \operatorname{csch}^{-1} \frac{v}{a} = \sinh^{-1} \frac{a}{v},$$

the integrals (35)-(37) may also be expressed in terms of the functions most convenient for use of the table of Art. 212.

ILLUSTRATIVE EXAMPLE. Derive (37) by means of the substitution $v = a \operatorname{csch} z$. (Compare Art. 135.)

Solution. We have

$$\sqrt{v^2 + a^2} = \sqrt{a^2 \operatorname{csch}^2 z + a^2} = a \operatorname{ctnh} z. \quad \text{By (2), Art. 211}$$

Also

$$dv = -a \operatorname{csch} z \operatorname{ctnh} z \, dz. \quad \text{By XXXII}$$

$$\text{Therefore} \quad \int \frac{dv}{v \sqrt{v^2 + a^2}} = \int \frac{-a \operatorname{csch} z \operatorname{ctnh} z \, dz}{a \operatorname{csch} z \cdot a \operatorname{ctnh} z} = -\frac{1}{a} z + C.$$

Since $z = \operatorname{csch}^{-1} \frac{v}{a}$, we have (37).

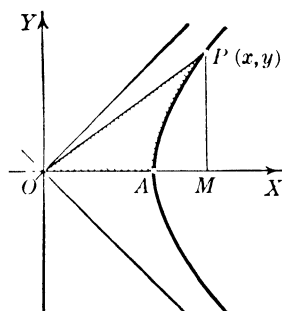
PROBLEMS

1. In the figure the curve is the equilateral hyperbola $x^2 - y^2 = a^2$. Using Art. 142, prove that

$$(a) \text{ area } AMP = \text{triangle } OMP - \frac{1}{2} a^2 \cosh^{-1} \frac{x}{a};$$

$$(b) \text{ sector } OAP = \frac{1}{2} a^2 \cosh^{-1} \frac{x}{a} = \frac{1}{2} a^2 v,$$

if $x = a \cosh v$. (Thus we have an alternative proof of the theorem of Art. 215.)



2. Derive each of the following power series by integration (Art. 196).

$$(a) \tanh^{-1} x = x + \frac{1}{3} x^3 + \frac{1}{5} x^5 + \cdots + \frac{x^{2n-1}}{2n-1} + \cdots \quad (x^2 < 1)$$

$$(b) \sinh^{-1} x = x - \frac{1}{2} \frac{x^3}{3} + \frac{1 \cdot 3}{2 \cdot 4} \frac{x^5}{5} - \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6} \frac{x^7}{7} + \cdots \quad (x^2 < 1)$$

Work out the following integrals.

$$3. \int \sinh^{-1} x \, dx = x \sinh^{-1} x - \sqrt{1 + x^2} + C.$$

$$4. \int \tanh^{-1} x \, dx.$$

$$5. \int x \cosh^{-1} x \, dx.$$

Work out, using hyperbolic functions.

$$6. \int_0^1 \frac{dx}{\sqrt{16x^2 + 9}}.$$

$$7. \int_0^2 \frac{dx}{25 - 4x^2}.$$

$$8. \int_3^5 \sqrt{x^2 - 9} \, dx.$$

9. Find the length of arc for the parabola $x^2 = 4y$ from $(0, 0)$ to $(4, 4)$, using hyperbolic functions. Ans. $\sqrt{20} + \sinh^{-1} 2 = 5.92$.

10. Find the area bounded by the catenary $y = a \cosh \frac{x}{a}$ and the line $y = 2a$.

11. The downward acceleration a of a falling body is given by $a = 32 - \frac{1}{2} v^2$, and $v = 0$, $s = 0$, when $t = 0$. Find v and s .

Ans. $v = 8 \tanh 4t$, $s = 2 \ln \cosh 4t$.

221. The gudermannian. The function $\text{arc tan} (\sinh v)$, which occurs frequently in mathematics (for example, in (1), Illustrative Example, Art. 219), is called the *gudermannian** of v . The symbol used is $\text{gd } v$ (read "gudermannian of v "). Thus

$$(1) \quad \text{gd } v = \text{arc tan} (\sinh v).$$

The derivative is

$$\text{XXXIX} \quad \frac{d}{dx} \text{gd } v = \text{sech } v \frac{dv}{dx},$$

assuming v to be a function of x .

Proof. Differentiating (1), we get

$$\frac{d}{dv} \text{gd } v = \frac{\cosh v}{1 + \sinh^2 v}. \quad \text{By XXII and XXVII}$$

$$\text{But} \quad 1 + \sinh^2 v = \cosh^2 v, \quad \text{by (B)}$$

$$\text{and} \quad \frac{1}{\cosh v} = \text{sech } v. \quad \text{By (1), Art. 211}$$

$$\text{Then} \quad \frac{d}{dx} \text{gd } v = \text{sech } v \frac{dv}{dx}. \quad \text{By (A), Art. 38}$$

From the definition (1) and Art. 77, we have

$$(2) \quad \text{gd } (0) = 0; \text{gd } (-v) = -\text{gd } v; \text{gd } \left(\frac{1}{2} \pi \right) = \frac{1}{2} \pi; \text{gd } (-\infty) = -\frac{1}{2} \pi.$$

When v increases, $\text{gd } v$ increases (since $\text{sech } v > 0$). Its value lies between $-\frac{1}{2} \pi$ and $+\frac{1}{2} \pi$. Some values are given in the accompanying table.

By (1), Art. 219,

$$(40) \quad \int \text{sech } v \, dv = \text{gd } v + C.$$

To find the inverse function (Art. 39) let

$$(3) \quad \phi = \text{arc tan} (\sinh v), \quad \left(-\frac{1}{2} \pi < \phi < \frac{1}{2} \pi \right)$$

and solve for v . The result is

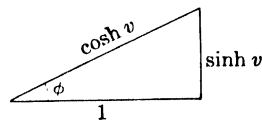
$$(4) \quad v = \sinh^{-1} (\tan \phi).$$

From (3) we have $\tan \phi = \sinh v$. Since $\cosh^2 v = 1 + \sinh^2 v$, by (B), the trigonometric functions of ϕ , when $v > 0$, can be read off from the accompanying right triangle.

Thus $\sin \phi = \tanh v$, $\cos \phi = \text{sech } v$, etc.

The inverse function † (4) may be written

$$(5) \quad v = \ln (\sec \phi + \tan \phi).$$



* Named after the mathematician Gudermann. His papers were published in 1830.

† The symbol $\text{gd}^{-1} \phi$ is used by some writers ($v = \text{gd}^{-1} \phi$).

Proof. Replace x in (F), Art. 216, by $\tan \phi$, and note that $1 + \tan^2 \phi$ is equal to $\sec^2 \phi$, by (2), p. 2.

Conversely, given (5), then $\phi = \text{gd } v$.

Proof. Changing to exponentials, (5) becomes

$$\sec \phi + \tan \phi = e^v, \quad \text{or} \quad \tan \phi - e^v = -\sec \phi.$$

Squaring both members, substituting $\sec^2 \phi = 1 + \tan^2 \phi$, and reducing, the result is

$$-2 \tan \phi e^v + e^{2v} = 1.$$

Solving for $\tan \phi$, we get

$$\tan \phi = \frac{e^v - e^{-v}}{2} = \sinh v. \quad \text{By (A)}$$

Hence

$$\phi = \text{arc tan } (\sinh v) = \text{gd } v. \quad \text{Q.E.D.}$$

ILLUSTRATIVE EXAMPLE. In the tractrix let

a = length of the tangent PT (constant by definition);

t = intercept of the tangent on the x -axis;

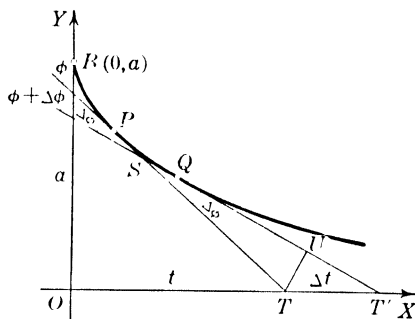
ϕ = angle between the tangent line directed upward and the y -axis;

$\phi = 0$ when $t = 0$.

Then $B(0, a)$ is on the curve.

To prove

$$(6) \quad \phi = \text{gd} \left(\frac{t}{a} \right).$$



Proof. When t is given, ϕ is determined. Hence ϕ is a function of t . Let the values of t and ϕ for the tangent line at Q , a point near P , be, respectively, $t + \Delta t (= OT')$ and $\phi + \Delta \phi$. Draw TU perpendicular to QT' . Let the tangent lines at P and Q intersect at S . Then in the right triangles UTT' and STU we have

$$TU = TT' \cos UTT'; \quad TU = TS \sin TSU.$$

Therefore

$$TT' \cos UTT' = TS \sin TSU.$$

But angle $UTT' = \phi + \Delta \phi$, angle $TSU = \Delta \phi$, $TT' = \Delta t$. Hence

$$\Delta t \cos (\phi + \Delta \phi) = TS \sin \Delta \phi.$$

Let Q move along the curve towards P , and let $\Delta \phi \rightarrow 0$. Then Δt and $\Delta \phi$ are infinitesimals. Also S approaches P and $TS \rightarrow a$. Hence, by the Replacement Theorem, Art. 98, and (B), Art. 68, we have

$$dt \cos \phi = a d\phi, \quad \text{or} \quad d \frac{t}{a} = \sec \phi d\phi.$$

Integrating, and remembering that $\phi = 0$ when $t = 0$, we get

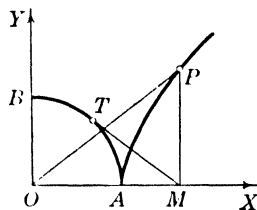
$$\frac{t}{a} = \ln (\sec \phi + \tan \phi).$$

Therefore, by (5),

$$\phi = \text{gd} \left(\frac{t}{a} \right). \quad \text{Q.E.D.}$$

PROBLEMS

1. The figure shows the circle $x^2 + y^2 = 1$ and equilateral hyperbola $x^2 - y^2 = 1$ in the first quadrant. From M , the foot of the ordinate MP of any point P on the hyperbola, draw MT tangent to the circle. Let $\frac{1}{2}v$ = area of the hyperbolic sector OAP (Art. 215), and ϕ = angle AOT . Prove $\phi = \text{gd } v$.



2. Prove

(a) $\text{gd } v = 2 \arctan e^v - \frac{1}{2} \pi$;

(b) $\int \sinh v \tanh v \, dv = \sinh v - \text{gd } v + C$.

3. Draw the graph of $y = \text{gd } x$. Calculate y and y' when $x = 1$. See figure.

Ans. $y = 0.86$, $y' = 0.65$.

4. In the Illustrative Example, p. 436, if P is (x, y) , prove that

$$x = t - a \sin \phi, \quad y = a \cos \phi.$$

From these and (6) derive the parametric equations

$$x = t - a \tanh \frac{t}{a}, \quad y = a \operatorname{sech} \frac{t}{a}$$

for the tractrix. Find the rectangular equation also.

5. Derive $\int \operatorname{sech}^3 v \, dv = \frac{1}{2} \operatorname{sech} v \tanh v + \frac{1}{2} \text{gd } v + C$.

6. If the length of the tangent of a curve (Art. 43) is constant ($= a$),

(a) prove $\frac{dy}{dx} = -\frac{y}{\sqrt{a^2 - y^2}}$.

(b) Integrate by the hyperbolic substitution $y = a \operatorname{sech} \frac{t}{a}$ and the con-

dition $x = 0$ when $t = 0$, and in this way derive the equations of the tractrix in Problem 4.

7. Evaluate each of the following by differentiation.

(a) $\lim_{x \rightarrow 0} \frac{\text{gd } x - x}{x^3}$;

(b) $\lim_{x \rightarrow 0} \frac{\text{gd } x - \sin x}{x^5}$.

Ans. (a) $-\frac{1}{6}$; (b) $\frac{1}{30}$.

8. Using the expansion of Problem 14, Art. 215, we have

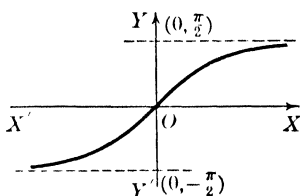
$$\text{gd } x = x - \frac{1}{6} x^3 + \frac{1}{24} x^5 - \frac{61}{40} x^7 + \dots$$

Calculate the value of $\text{gd } 0.5$ to four places of decimals. Ans. 0.4804.

9. The equation (5), p. 435, may be written

$$v = \ln \tan \left(\frac{1}{4} \pi + \frac{1}{2} \phi \right).$$

Prove this statement, making use of (2), (4), and (5), pp. 2, 3.



222. Mercator's Chart. The figure shows a portion (one eighth) of a sphere representing the earth. North Pole N , equator EF , longitude θ_1 and latitude ϕ_1 of the point P_1 are indicated. Q , with longitude $\theta_1 + \Delta\theta$, latitude $\phi_1 + \Delta\phi$, is a second point, near P_1 on the curve P_1QV . The meridians and parallels through P_1 and Q are shown. They form the quadrilateral P_1SQR . We seek expressions for the circular arcs RQ and P_1R .

Since O is the center of the equal arcs RQ and P_1S , each with central angle $\Delta\phi$, we have

$$(1) \text{ arc } RQ = \text{arc } P_1S = a \Delta\phi.$$

Also, C is the center of arc P_1R , with central angle $\Delta\theta$. Hence $\text{arc } P_1R = CP_1 \cdot \Delta\theta$. But, in the right triangle OP_1C (right angle at C), $CP_1 = a \cos \phi_1$. Hence

$$\text{arc } P_1R = a \cos \phi_1 \Delta\theta.$$

The line P_1R' is tangent at P_1 to the parallel P_1R . The line P_1T is tangent* at P_1 to the curve P_1QV . The angle at P_1 between the curve and the parallel is the angle $R'P_1T$. Then

$$(2) \quad \tan R'P_1T = \sec \phi_1 \left(\frac{d\phi}{d\theta} \right)_1,$$

the value of the derivative being found from the equation

$$(3) \quad \theta = f(\phi)$$

satisfied by the latitude and longitude of each point of the curve P_1QV .

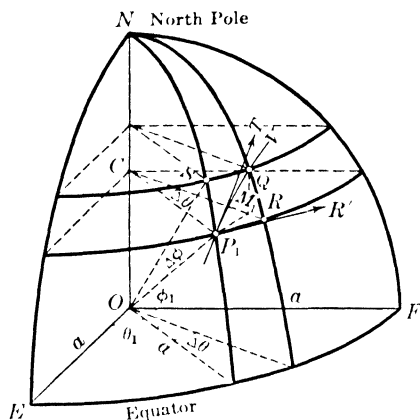
Proof of (2). By the Replacement Theorem, Art. 98, it can be shown † that

$$(4) \quad \tan R'P_1T = \lim_{\Delta\theta \rightarrow 0} \frac{\text{arc } RQ}{\text{arc } P_1R}.$$

Substituting the values from (1), we get (2).

* Defined as in Art. 28 as the limiting position of the secant through P_1 and Q when Q approaches P_1 along the curve P_1Q .

† The details are indicated in the Additional Problems (p. 143). Note that arc RQ and arc P_1R are, respectively, opposite and adjacent to the angle at P_1 in the curvilinear triangle P_1RQ .



On Mercator's* Chart of the earth's surface the point with latitude ϕ , longitude θ , is represented by the point (x, y) such that

$$(5) \quad x = \theta, \quad y = \ln (\sec \phi + \tan \phi),$$

or, inversely,

$$(6) \quad \theta = x, \quad \phi = \operatorname{gd} y. \quad \text{By Art. 221}$$

In (5) and (6), θ and ϕ are expressed in radians. Meridians ($\theta = \text{constant}$) are represented on the chart by lines parallel to the y -axis, parallels ($\phi = \text{constant}$) by lines parallel to the x -axis. The curve (3) is given by the parametric equations

$$(7) \quad x = f(\phi), \quad y = \ln (\sec \phi + \tan \phi).$$

Theorem. *The angle between a curve on the sphere and an intersecting parallel is unchanged by mapping.*

Proof. Let (x_1, y_1) be the point on (7) where $\phi = \phi_1$. The parallel becomes the line $y = y_1$ on the chart. Hence we have to prove that the curve (7) is such that

$$(8) \quad \left(\frac{dy}{dx}\right)_1 = \sec \phi_1 \left(\frac{d\phi}{d\theta}\right)_1. \quad \text{Using (2)}$$

From (7) and (3), we get

$$\frac{dy}{d\phi} = \sec \phi, \quad \frac{dx}{d\phi} = f'(\phi) = \frac{d\theta}{d\phi}.$$

Then (8) follows from (A), Art. 81, and (C), Art. 39. Q.E.D.

Two important corollaries follow.

Cor. I. The angle at P_1 on the sphere formed by two curves, P_1QR and $P_1Q'R'$, will equal the angle on the chart at (x_1, y_1) formed by the corresponding curves. Hence angles remain unchanged by mapping.

Cor. II. A straight line on the chart with slope $\tan \alpha$ corresponds to a curve on the sphere cutting all parallels under the same angle α . This curve is called a *rhumb line* (or *loxodrome*).

Along a rhumb line

$$(9) \quad \phi = \operatorname{gd}(\theta \tan \alpha + b).$$

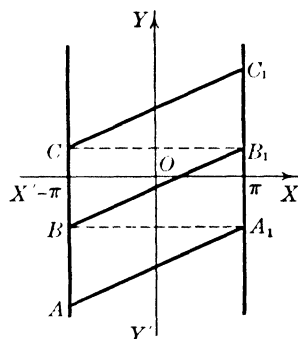
This follows from (6) and $y = x \tan \alpha + b$. The course of a ship proceeding always in the same direction lies along a rhumb line. In the representation (5), θ , and therefore x , has values from $-\pi$ to $+\pi$, inclusive. On the other hand, y may have any value (Art. 221). Hence the entire surface of the earth is mapped on the strip of the xy -plane determined by the lines $x = -\pi$ and $x = +\pi$.

* Gerardus Mercator (1512–1594), a noted cartographer, published his Chart of the World in 1569. His name is the Latinized form of Gerhard Kremer.

By the table of Art. 221 we may find the latitude in degrees of the parallels which are given on the chart by the lines $y = \text{constant}$.

y	0	0.5	1.0	1.5	2	3	4	5
lat.	0°	27° 31'	49° 36'	64° 51'	74° 35'	84° 18'	87° 54'	89° 14'

A rhumb line is represented on the map by a series of parallel line segments such as AA_1 , BB_1 , CC_1 , etc. in the figure, where BA_1 , CB_1 , etc. are parallel to the x -axis. The representation is "conformal"; that is, the *shape* of small areas is preserved. This follows from Cor. 1. For example, a triangular figure * on the earth's surface bounded by rhumb lines will be a triangle on the map, and corresponding angles in the two figures will be equal. But the distortion of an area on the earth's surface by mapping depends upon its distance from the equator. Problem 4, p. 442, brings out this point.



223. Relations between trigonometric and hyperbolic functions. Let the exponent v of the exponential function e^v be a *complex number* $x + iy$ (x and y real numbers; $i = \sqrt{-1}$). Then we assume as a definition

$$(1) \quad e^{x+iy} = e^x e^{iy} = e^x (\cos y + i \sin y).$$

If $x = 0$, we have (see p. 391)

$$(2) \quad e^{iy} = \cos y + i \sin y.$$

Change y to $-y$. Then (2) becomes

$$(3) \quad e^{-iy} = \cos y - i \sin y.$$

Solving (2) and (3) for $\sin y$ and $\cos y$, the results are

$$(4) \quad \sin y = \frac{e^{iy} - e^{-iy}}{2i}, \quad \cos y = \frac{e^{iy} + e^{-iy}}{2}.$$

Thus the sine and cosine of a real variable are expressed in terms of exponential functions with imaginary exponents.

Formulas (4) and (A) suggest definitions of the functions concerned when the variable is any complex number z . These definitions are

$$(5) \quad \sin z = \frac{e^{iz} - e^{-iz}}{2i}, \quad \cos z = \frac{e^{iz} + e^{-iz}}{2},$$

$$\sinh z = \frac{e^z - e^{-z}}{2}, \quad \cosh z = \frac{e^z + e^{-z}}{2}.$$

* The lines $x = -\pi$ and $x = +\pi$ represent the same meridian (180° W. or 180° E.). It is assumed that this meridian does not cross the curvilinear triangle. In the figure, A_1 and B represent the same point on the earth, as do also B_1 and C .

The other trigonometric and hyperbolic functions of z are defined by the same ratios as are used when the variable is a real number. From (5) we may prove the following:

$$(L) \quad \sinh iz = i \sin z, \quad \cosh iz = \cos z.$$

$$\left[\sinh iz = \frac{e^{iz} - e^{-iz}}{2} = i \sin z, \text{ using (5); etc.} \right]$$

From (L), by division, we get

$$(6) \quad \tanh iz = i \tan z.$$

The similarity of many formulas in this chapter to others for trigonometric functions is explained by the relations (L) and (6) (see Illustrative Example 2). The right-hand members of (5) are expressible as complex numbers whose real parts involve only trigonometric and hyperbolic functions of real variables. This appears below in Illustrative Example 1.

ILLUSTRATIVE EXAMPLE 1. Derive the formula

$$(7) \quad \sinh(x + iy) = \sinh x \cos y + i \cosh x \sin y.$$

Solution. By (5), if $z = x + iy$, we have

$$(8) \quad \sinh(x + iy) = \frac{e^{x+iy} - e^{x-iy}}{2} \\ (9) \quad = \frac{e^x(\cos y + i \sin y) - e^x(\cos y - i \sin y)}{2}. \quad \text{By (1)}$$

By (1), Art. 210, if $v = x$, we have

$$e^x = \cosh x + \sinh x, \quad e^{-x} = \cosh x - \sinh x.$$

Substitute these values in (9), and reduce. The result is (7). Changing i to $-i$, (7) becomes

$$\sinh(x - iy) = \sinh x \cos y - i \cosh x \sin y.$$

The form of the right-hand member here and in (7) should be noticed.

ILLUSTRATIVE EXAMPLE 2. Prove directly by (5) the relations

$$\sin^2 z + \cos^2 z = 1, \quad \cosh^2 z - \sinh^2 z = 1.$$

Solution. The details are the same as in the proof of (B), Art. 210.

The first relation may be derived from the second as follows:

Let $z = iv$. Then $\cosh^2 iv - \sinh^2 iv = 1$. But, by (L), $\cosh iv = \cos v$, $\sinh iv = i \sin v$. Hence $\cos^2 v + \sin^2 v = 1$.

PROBLEMS

1. Using differentials, show that the distance apart on Mercator's Chart of the lines parallel to the x -axis which represent the parallels at latitudes ϕ_1 and $\phi_1 + \Delta\phi$, respectively, varies as $\sec \phi_1$.

2. Along a rhumb line $\phi = \text{gd}(\theta \tan \alpha + b)$. Prove by differentiation that $\tan \alpha = \sec \phi \frac{d\phi}{d\theta}$.

3. The altitude h of the zone on the sphere bounded by the parallels $\phi = \phi_2$, $\phi = \phi_1$ ($\phi_2 > \phi_1$) is $a(\sin \phi_2 - \sin \phi_1)$ (see figure, p. 438). If $y = y_2$, $y = y_1$ are the corresponding parallels on the map, prove the following.

$$(a) \quad h = a(\tanh y_2 - \tanh y_1);$$

$$(b) \quad dy = \frac{1}{a} \sec^2 \phi_1 dh, \text{ if } \phi_2 = \phi_1 + d\phi.$$

4. Using (b), Problem 3, show that equal zones of small altitude whose lower bases are parallels at latitudes 0° , 30° , 45° , 60° , respectively, map into rectangles whose areas are as $3 : 4 : 6 : 12$. (The area of a zone equals its altitude times the circumference of a great circle.)

5. Describe the direction of a curve on the sphere (a) if $\frac{d\phi}{d\theta} = 0$; (b) if $\frac{d\phi}{d\theta}$ becomes infinite.

6. Derive each of the following formulas by the method used in Illustrative Example 1.

$$(a) \quad \cosh(x + iy) = \cosh x \cos y + i \sinh x \sin y;$$

$$(b) \quad \sin(x + iy) = \sin x \cosh y + i \cos x \sinh y;$$

$$(c) \quad \cos(x + iy) = \cos x \cosh y - i \sin x \sinh y.$$

From these write the values of $\cosh(x - iy)$, $\sin(x - iy)$, $\cos(x - iy)$.

$$7. \text{ Prove } (a) \quad \sinh\left(i\frac{\pi}{2} \pm x\right) = i \cosh x;$$

$$(b) \quad \cosh\left(i\frac{\pi}{2} \pm x\right) = \pm i \sinh x.$$

8. Evaluate each of the following to two places of decimals.

$$(a) \quad \sinh(1.5 + i);$$

$$(b) \quad \cosh(1 - i);$$

$$(c) \quad \cos(0.8 + 0.5i);$$

$$(d) \quad \sin(0.5 + 0.8i).$$

Ans. (a) $1.15 + 1.98i$; (c) $0.78 - 0.37i$.

ADDITIONAL PROBLEMS

1. In the figure of Art. 222, P_1M_1 is drawn perpendicular to CR , and therefore perpendicular to the plane of the meridian NQR . Then triangle P_1QM_1 is a right triangle (the chord P_1Q is not shown), and $\tan M_1P_1Q = \frac{M_1Q}{P_1M_1}$. When $\Delta\theta \rightarrow 0$, the line P_1M_1 (produced) approaches the tangent P_1R' , and angle M_1P_1Q approaches angle $R'P_1T$. Therefore

$$(10) \quad \tan R'P_1T = \lim_{\Delta\theta \rightarrow 0} \frac{M_1Q}{P_1M_1}.$$

Compare with (4), Art. 222, and show that

$$(a) \lim_{\Delta\theta \rightarrow 0} \frac{P_1 M_1}{\text{arc } P_1 R} = 1 \quad (\text{see Fig. 1});$$

$$(b) \lim_{\Delta\theta \rightarrow 0} \frac{M_1 Q}{\text{arc } RQ} = 1 \quad (\text{see Fig. 2, which shows$$

the plane of the meridian NQR). In triangle M_1QR show that M_1R is an infinitesimal of higher order than QR when $\Delta\theta$ and $\Delta\phi$ are of the same order (Art. 99). Then see Problem, p. 148.

Using (a) and (b) and the Replacement Theorem, Art. 98, (10) becomes (4), Art. 222.

2. If ds_1 is the element of the length of arc for a curve on the sphere of Art. 222, prove that $ds_1^2 = a^2(d\phi^2 + \cos^2 \phi d\theta^2)$. (In the figure of Art. 222, $(\text{chord } P_1Q)^2 = \overline{P_1M_1}^2 + \overline{M_1Q}^2$ and $\lim_{\Delta\theta \rightarrow 0} \frac{\text{chord } P_1Q}{\text{arc } P_1Q} = 1$.)

3. If ds is the differential of the arc of a curve on Mercator's Chart, show that $ds^2 = \sec^2 \phi(d\phi^2 + \cos^2 \phi d\theta^2)$. (Comparing with Problem 2, we have $ds_1^2 = a^2 \cos^2 \phi ds^2$.)

4. Find the length of a rhumb line between points whose difference of latitude is $\Delta\phi$. *Ans.* $a \csc \alpha \Delta\phi$. (a = radius of the earth.)

5. Prove that the first four formulas in (4), p. 3, and (D), (E), Art. 213, hold when x, y, v, w are replaced by complex numbers. (Use the definitions (5).)

6. Prove the formulas of Problem 6, p. 442, by using the results in Additional Problem 5 and (L).

$$7. \text{ Prove that } \tanh(x + iy) = \frac{\sinh 2x + i \sin 2y}{\cosh 2x + \cos 2y}.$$

8. Derive the formula for $\tan(x + iy)$ from the result in the preceding problem.

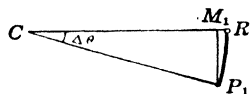


FIG. 1

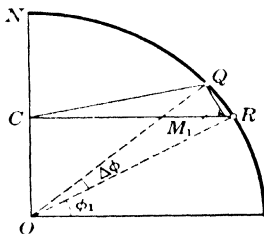


FIG. 2

CHAPTER XXIII

PARTIAL DIFFERENTIATION

224. Functions of several variables. Continuity. The preceding chapters have been devoted to applications of the calculus to functions of one variable. We now turn to functions of more than one independent variable. Simple examples of such functions are afforded by formulas from elementary mathematics. Thus, in the relation for the volume v of a right circular cylinder,

$$(1) \quad v = \pi r^2 y,$$

v is a function of the two independent variables x ($=$ radius) and y ($=$ altitude). Again, in the formula for the area u of an oblique plane triangle,

$$(2) \quad u = \frac{1}{2} xy \sin \alpha,$$

u is a function of the three independent variables x , y , and α , representing, respectively, two sides and the included angle.

Obviously, in (1), as well as in (2), the values which can be assigned to the variables in the right-hand member are entirely independent of one another.

The relation

$$(3) \quad z = f(x, y)$$

can be represented graphically by a surface, the locus of the equation (3) obtained by interpreting x , y , z as rectangular coördinates, as in solid analytic geometry. This surface is the graph of the function of two variables, $f(x, y)$.

A function $f(x, y)$ of two independent variables x and y is defined as *continuous* for $x = a$, $y = b$, when

$$(A) \quad \lim_{\substack{x \rightarrow a \\ y \rightarrow b}} f(x, y) = f(a, b),$$

no matter in what way x and y approach their respective limits a and b .

This definition is sometimes roughly summed up in the statement that *a very small change in one or both of the variables produces a very small change in the value of the function*.*

* This will be better understood if the student again reads over Art. 17 on continuous functions of a single variable.

We may illustrate this geometrically by considering the surface represented by the equation

$$(3) \quad z = f(x, y).$$

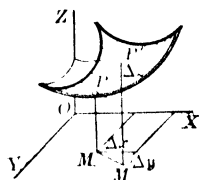
Consider a fixed point P on the surface where $x = a$ and $y = b$.

Denote by Δx and Δy the increments of the variables x and y , and by Δz the corresponding increment of the function z , the coördinates of P' being

$$(x + \Delta x, y + \Delta y, z + \Delta z).$$

At P the value of the function is

$$z = f(a, b) = MP.$$



If the function is continuous at P , then however Δx and Δy may approach zero as a limit, Δz will also approach zero as a limit. That is, $M'P'$ will approach coincidence with MP , the point P' approaching the point P on the surface from any direction whatever.

A similar definition holds for a continuous function of more than two variables.

In what follows, only values of the variables are considered for which a function is continuous.

225. Partial derivatives. In the relation

$$(1) \quad z = f(x, y),$$

we may hold y fast and let x alone vary. Then z becomes a function of one variable x , and we may form its derivative in the usual manner. The notation is

$$\frac{\partial z}{\partial x} = \text{partial derivative of } z \text{ with respect to } x \text{ (} y \text{ remains constant).}^*$$

Similarly,

$$\frac{\partial z}{\partial y} = \text{partial derivative of } z \text{ with respect to } y \text{ (} x \text{ remains constant).}^*$$

Corresponding symbols are used for partial derivatives of functions of three or more variables.

In order to avoid confusion the round ∂ † has been generally adopted to indicate partial differentiation.

* The constant values are substituted in the function before differentiating.

† Introduced by Jacobi (1804–1851).

ILLUSTRATIVE EXAMPLE 1. Find the partial derivatives of $z = ax^2 + 2bxy + cy^2$.

Solution. $\frac{\partial z}{\partial x} = 2ax + 2by$, treating y as a constant,
 $\frac{\partial z}{\partial y} = 2bx + 2cy$, treating x as a constant.

ILLUSTRATIVE EXAMPLE 2. Find the partial derivatives of $u = \sin(ax + by + cz)$.

Solution. $\frac{\partial u}{\partial x} = a \cos(ax + by + cz)$, treating y and z as constants,
 $\frac{\partial u}{\partial y} = b \cos(ax + by + cz)$, treating x and z as constants,
 $\frac{\partial u}{\partial z} = c \cos(ax + by + cz)$, treating y and x as constants.

Referring to (1), we have, in the notations commonly used,

$$\frac{\partial z}{\partial x} = \frac{\partial}{\partial x} f(x, y) = \frac{\partial f}{\partial x} = f_x(x, y) = f_x = z_x;$$

$$\frac{\partial z}{\partial y} = \frac{\partial}{\partial y} f(x, y) = \frac{\partial f}{\partial y} = f_y(x, y) = f_y = z_y.$$

Similar notations are used for functions of any number of variables.

Referring to Art. 24, we shall have

$$(2) \quad f_x(x, y_0) = \lim_{\Delta x \rightarrow 0} \frac{f(x + \Delta x, y_0) - f(x, y_0)}{\Delta x},$$

$$(3) \quad f_y(x_0, y) = \lim_{\Delta y \rightarrow 0} \frac{f(x_0, y + \Delta y) - f(x_0, y)}{\Delta y}.$$

226. Partial derivatives interpreted geometrically. Let the equation of the surface shown in the figure be

$$z = f(x, y).$$

Pass a plane $EFGH$ through the point P (where $x = a$ and $y = b$) on the surface parallel to the XOZ -plane. Since the equation of this plane is

$$y = b,$$

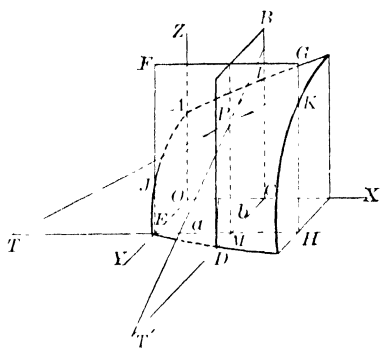
the equation of the curve of intersection JPK with the surface is

$$z = f(x, b),$$

if we consider EF as the axis of Z and EH as the axis of X . In this

plane $\frac{\partial z}{\partial x}$ means the same as $\frac{dz}{dx}$, and we have

$$(1) \quad \frac{\partial z}{\partial x} = \tan MTP = \text{slope of curve of intersection } JK \text{ at } P.$$



Similarly, if we pass the plane BCD through P parallel to the YOZ -plane, its equation is $x = a$,

and for the curve of intersection DPI , $\frac{\partial z}{\partial y}$ means the same as $\frac{dz}{dy}$. Hence

$$(2) \quad \frac{\partial z}{\partial y} = -\tan MT'P = \text{slope of curve of intersection } DI \text{ at } P.$$

ILLUSTRATIVE EXAMPLE. Given the ellipsoid $\frac{x^2}{24} + \frac{y^2}{12} + \frac{z^2}{6} = 1$; find the slope of the curve of intersection of the ellipsoid made (a) by the plane $y = 1$ at the point where $x = 4$ and z is positive; (b) by the plane $x = 2$ at the point where $y = 3$ and z is positive.

Solution. Considering y as constant,

$$\frac{2x}{24} + \frac{2z}{6} \frac{\partial z}{\partial x} = 0, \quad \text{or} \quad \frac{\partial z}{\partial x} = -\frac{x}{4z}.$$

$$\text{When } x \text{ is constant, } \frac{2y}{12} + \frac{2z}{6} \frac{\partial z}{\partial y} = 0, \quad \text{or} \quad \frac{\partial z}{\partial y} = -\frac{y}{2z}.$$

$$(a) \text{ When } y = 1 \text{ and } x = 4, z = \sqrt{\frac{3}{2}}, \quad \therefore \frac{\partial z}{\partial x} = -\sqrt{\frac{2}{3}}. \quad \text{Ans.}$$

$$(b) \text{ When } x = 2 \text{ and } y = 3, z = \frac{1}{\sqrt{2}}, \quad \therefore \frac{\partial z}{\partial y} = -\frac{3}{2}\sqrt{2}. \quad \text{Ans.}$$

PROBLEMS

Work out the following partial derivatives.

$$1. \quad z = Ax^2 + Bxy + Cy^2 + Dx + Ey + F.$$

$$\text{Ans. } \frac{\partial z}{\partial x} = 2Ax + By + D; \quad \frac{\partial z}{\partial y} = Bx + 2Cy + E.$$

$$2. \quad f(x, y) = Ax^3 + 3Bx^2y + 3Cxy^2 + Dy^3.$$

$$\text{Ans. } f_x(x, y) = 3(Ax^2 + 2Bxy + Cy^2); \\ f_y(x, y) = 3(Bx^2 + 2Cxy + Dy^2).$$

$$3. \quad f(x, y) = \frac{Ax + By}{Cx + Dy} \quad \text{Ans. } \frac{\partial f}{\partial x} = \frac{(AD - BC)y}{(Cx + Dy)^2}; \quad \frac{\partial f}{\partial y} = \frac{(BC - AD)x}{(Cx + Dy)^2}.$$

$$4. \quad u = xy + yz + zx. \quad \text{Ans. } u_x = y + z; \quad u_y = x + z; \quad u_z = x + y.$$

$$5. \quad f(x, y) = (x + y) \sin(x - y).$$

$$\text{Ans. } f_x(x, y) = \sin(x - y) + (x + y) \cos(x - y); \\ f_y(x, y) = \sin(x - y) - (x + y) \cos(x - y).$$

$$6. \quad \rho = \sin 2\theta \cos 3\phi. \quad \text{Ans. } \frac{\partial \rho}{\partial \theta} = 2 \cos 2\theta \cos 3\phi;$$

$$\frac{\partial \rho}{\partial \phi} = -3 \sin 2\theta \sin 3\phi.$$

$$7. \quad \rho = e^{\theta + \phi} \cos(\theta - \phi). \quad \text{Ans. } \frac{\partial \rho}{\partial \theta} = e^{\theta + \phi} \{\cos(\theta - \phi) - \sin(\theta - \phi)\};$$

$$\frac{\partial \rho}{\partial \phi} = e^{\theta + \phi} \{\cos(\theta - \phi) + \sin(\theta - \phi)\}.$$

Find the partial derivatives of the following functions.

8. $f(x, y) = 3x^4 - 4x^3y + 6x^2y^2$. 11. $f(x, y) = (x + 2y) \tan(2x + y)$.

9. $u = \frac{x + 2y}{y + 2z}$.

12. $\rho = \tan 2\theta \cot 4\phi$.

10. $z = e^{\frac{x}{y}} \ln \frac{y}{x}$.

13. $\rho = e^{-\theta} \cos \frac{\phi}{\theta}$.

14. If $f(x, y) = 2x^2 - 3xy + 4y^2$, show that $f_x(2, 3) = -1$, $f_y(2, 3) = 18$.

15. If $f(x, y) = \frac{2x}{x - y}$, show that $f_x(3, 1) = -\frac{1}{2}$, $f_y(3, 1) = \frac{3}{2}$.

16. If $f(x, y) = e^{-x} \sin(x + 2y)$, show that $f_x\left(0, \frac{\pi}{4}\right) = -1$, $f_y\left(0, \frac{\pi}{4}\right) = 0$.

17. If $u = Ax^4 + 2Bx^2y^2 + Cy^4$, show that $x \frac{\partial u}{\partial x} + y \frac{\partial u}{\partial y} = 4u$.

18. If $u = \frac{x^2y^2}{x + y}$, show that $x \frac{\partial u}{\partial x} + y \frac{\partial u}{\partial y} = 3u$.

19. If $u = x^2y + y^2z + z^2x$, show that $\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} = (x + y + z)^2$.

20. If $u = \frac{Ax^n + By^n}{Cx^2 + Dy^2}$, show that $x \frac{\partial u}{\partial x} + y \frac{\partial u}{\partial y} = (n - 2)u$.

21. The area of a triangle is given by the formula $K = \frac{1}{2}bc \sin A$. Given $b = 10$ in., $c = 20$ in., $A = 60^\circ$.

(a) Find the area.

(b) Find the rate of change of the area with respect to the side b if c and A remain constant.

(c) Find the rate of change of the area with respect to the angle A if b and c remain constant.

(d) Using the rate found in (c), calculate approximately the change in area if the angle is increased by one degree.

(e) Find the rate of change of c with respect to b if the area and the angle remain constant.

22. The law of cosines for any triangle is $a^2 = b^2 + c^2 - 2bc \cos A$. Given $b = 10$ in., $c = 15$ in., $A = 60^\circ$.

(a) Find a .

(b) Find the rate of change of a with respect to b if c and A remain constant.

(c) Using the rate found in (b), calculate approximately the change in a if b is decreased by 1 in.

(d) Find the rate of change of a with respect to A if b and c remain constant.

(e) Find the rate of change of c with respect to A if a and b remain constant.

227. The total differential. We have already considered the differential of a function of one variable in Art. 91. Thus, if

$$y = f(x),$$

we defined and proved

$$(1) \quad dy = f'(x)\Delta x = \frac{dy}{dx} \Delta x = \frac{dy}{dx} dx.$$

We shall next consider a function of two variables. Consider the function

$$(2) \quad u = f(x, y).$$

Let Δx and Δy be the increments of x and y respectively, and let Δu be the corresponding increment of u . Then

$$(3) \quad \Delta u = f(x + \Delta x, y + \Delta y) - f(x, y)$$

is called the *total increment* of u .

Adding and subtracting $f(x, y + \Delta y)$ in the second member,

$$(4) \quad \Delta u = [f(x + \Delta x, y + \Delta y) - f(x, y + \Delta y)] \\ + [f(x, y + \Delta y) - f(x, y)].$$

Applying the Theorem of Mean Value (D), Art. 116, to each of the two differences on the right-hand side of (4), we get, for the first difference,

$$(5) \quad f(x + \Delta x, y + \Delta y) - f(x, y + \Delta y) = f_x(x + \theta_1 \Delta x, y + \Delta y)\Delta x.$$

[$a = x$, $\Delta a = \Delta x$, and since x varies while $y + \Delta y$ remains constant, we get the partial derivative with respect to x .]

For the second difference,

$$(6) \quad f(x, y + \Delta y) - f(x, y) = f_y(x, y + \theta_2 \Delta y)\Delta y.$$

[$a = y$, $\Delta a = \Delta y$, and since y varies while x remains constant, we get the partial derivative with respect to y .]

Substituting from (5) and (6) in (4) gives

$$(7) \quad \Delta u = f_x(x + \theta_1 \Delta x, y + \Delta y)\Delta x + f_y(x, y + \theta_2 \Delta y)\Delta y,$$

where θ_1 and θ_2 are positive proper fractions.

Since $f_x(x, y)$ and $f_y(x, y)$ are continuous functions of x and y , the coefficients of Δx and Δy in (7) will approach $f_x(x, y)$ and $f_y(x, y)$, respectively, as limits when Δx and Δy approach zero as common limits. Hence if ϵ and ϵ' are infinitesimals such that

$$\lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \epsilon = 0, \quad \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \epsilon' = 0,$$

we may write

$$(8) \quad f_x(x + \theta_1 \Delta x, y + \Delta y) = f_x(x, y) + \epsilon,$$

$$(9) \quad f_y(x, y + \theta_2 \Delta y) = f_y(x, y) + \epsilon',$$

and (7) will become

$$(10) \quad \Delta u = f_x(x, y)\Delta x + f_y(x, y)\Delta y + \epsilon\Delta x + \epsilon'\Delta y.$$

We then define as the *total differential* ($= du$) of u

$$(11) \quad du = f_x(x, y)\Delta x + f_y(x, y)\Delta y.$$

The right-hand member in (11) is the "principal part" of the right-hand member of (10), that is, du is a close approximate value of Δu for small values of Δx and Δy (compare Art. 92). Obviously, if $u = x$, (11) becomes $dx = \Delta x$. If $u = y$, (11) becomes $dy = \Delta y$. Substituting, then, in (11) for Δx and Δy their corresponding differentials, we obtain the important formula

$$(B) \quad du = f_x(x, y) dx + f_y(x, y) dy = \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial y} dy = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy,$$

which should be compared with (1) at the beginning of this article.

If u is a function of three variables, its total differential is

$$(C) \quad du = \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial y} dy + \frac{\partial u}{\partial z} dz;$$

and so on for any number of variables.

A geometric interpretation of (B) is given in Art. 238.

ILLUSTRATIVE EXAMPLE 1. Compute Δu and du for the function

$$(12) \quad u = 2x^2 + 3y^2,$$

when $x = 10$, $y = 8$, $\Delta x = 0.2$, $\Delta y = 0.3$, and compare the results.

Solution. Substitute in (12) for x , y , u , respectively, $x + \Delta x$, $y + \Delta y$, $u + \Delta u$, and proceed as below (compare Art. 27).

$$\begin{aligned} u + \Delta u &= 2(x + \Delta x)^2 + 3(y + \Delta y)^2 \\ &= 2x^2 + 3y^2 + 4x\Delta x + 6y\Delta y + 2(\Delta x)^2 + 3(\Delta y)^2. \\ u &= 2x^2 + 3y^2 \end{aligned}$$

$$(13) \quad \Delta u = 4x\Delta x + 6y\Delta y + 2(\Delta x)^2 + 3(\Delta y)^2.$$

Differentiating (12), we find

$$\frac{\partial u}{\partial x} = 4x, \quad \frac{\partial u}{\partial y} = 6y.$$

Substituting in (B), the result is

$$(14) \quad du = 4x dx + 6y dy.$$

Remembering that $\Delta x = dx$, $\Delta y = dy$, we see that the right-hand member in (14) is the "principal part" of the right-hand member in (13), for the additional terms are of the second degree in Δx or Δy . This statement illustrates (10) and (11) above (namely, $\epsilon = 2\Delta x$, $\epsilon' = 3\Delta y$).

Substituting the given values in (13) and (14), we get

$$(15) \quad \Delta u = 8 + 14.4 + 0.08 + 0.27 = 22.75;$$

$$(16) \quad du = 8 + 14.4 = 22.4.$$

Then $\Delta u - du = 0.35 = 1.6\%$ of Δu . *Ans.*

ILLUSTRATIVE EXAMPLE 2. Given $u = \arctan \frac{y}{x}$, find du .

Solution.
$$\frac{\partial u}{\partial x} = -\frac{y}{x^2 + y^2}, \quad \frac{\partial u}{\partial y} = \frac{x}{x^2 + y^2}.$$

Substituting in (B),
$$du = \frac{x dy - y dx}{x^2 + y^2}. \quad \text{Ans.}$$

PROBLEMS

Find the total differential of each of the following functions.

1. $z = 2x^3 - 4xy^2 + 3y^3$. *Ans.* $dz = (6x^2 - 4y^2)dx + (9y^2 - 8xy)dy$.

2. $u = \frac{Ax + By}{Cx + Dy}$.
$$du = \frac{(AD - BC)(y dx - x dy)}{(Cx + Dy)^2}.$$

3. $u = xy^2z^3$.
$$du = y^2z^3 dx + 2xyz^3 dy + 3xy^2z^2 dz.$$

4. $u = x^2 \cos 2y$. 5. $\theta = \arctan \frac{y}{x}$. 6. $u = (x - y) \ln(x + y)$.

7. If $x^2 + y^2 + z^2 = a^2$, show that $dz = -\frac{x dx + y dy}{z}$.

8. Find dz if $4x^2 - 9y^2 - 16z^2 = 100$.

9. Compute Δu and du for the function $u = x^2 - 3xy + 2y^2$ when $x = 2$, $y = -3$, $\Delta x = -0.3$, $\Delta y = 0.2$. *Ans.* $\Delta u = -7.15$, $du = -7.5$.

10. Compute du for the function $u = (x + y)\sqrt{x - y}$ when $x = 6$, $y = 2$, $dx = \frac{1}{4}$, $dy = -\frac{1}{2}$. *Ans.* 1.

11. Compute Δu and du for the function $u = xy + 2x - 4y$ when $x = 2$, $y = 3$, $\Delta x = 0.4$, $\Delta y = -0.2$.

12. Compute $d\rho$ for the function $\rho = c^{\frac{\theta}{2}} \sin(\theta - \phi)$ when $\theta = 0$, $\phi = \frac{1}{2}\pi$, $d\theta = 0.2$, $d\phi = -0.2$.

228. Approximation of the total increment. Small errors. Formulas (B) and (C) are used to calculate Δu approximately. Also, when the values of x and y are determined by measurement or experiment, and hence subject to small errors Δx and Δy , a close approximation to the error in u can be found by (B). (Compare Arts. 92, 93.)

ILLUSTRATIVE EXAMPLE 1. Find, approximately, the volume of tin in a thin cylindrical can without a top if the inside diameter and height are, respectively, 6 in. and 8 in., and the thickness is $\frac{1}{8}$ in.

Solution. The volume v of a solid right circular cylinder with diameter x and height y is

$$(1) \quad v = \frac{1}{4} \pi x^2 y.$$

Obviously, the exact volume of the can is the difference Δv between the volumes of two solid cylinders for which $x = 6\frac{1}{4}$, $y = 8\frac{1}{8}$, and $x = 6$, $y = 8$, respectively. Since only an approximate value is required, we calculate dv instead of Δv .

Differentiating (1), and using (B), we get

$$(2) \quad dv = \frac{1}{2} \pi xy \, dx + \frac{1}{2} \pi x^2 \, dy.$$

Substituting in (2) $x = 6$, $y = 8$, $dx = \frac{1}{4}$, $dy = \frac{1}{4}$, the result is

$$dv = 7\frac{1}{8} \pi = 22.4 \text{ cu. in.} \quad \text{Ans.}$$

The exact value is $\Delta v = 23.1$ cu. in.

ILLUSTRATIVE EXAMPLE 2. Two sides of an oblique plane triangle measured, respectively, 63 ft. and 78 ft., and the included angle measured 60° . These measurements were subject to errors whose maximum values are 0.1 ft. in each length and $1'$ in the angle. Find the approximate maximum error and the percentage error made in calculating the third side from these measurements.

Solution. Using the law of cosines ((7), Art. 2),

$$(3) \quad u^2 = x^2 + y^2 - 2xy \cos \alpha,$$

where x , y are the given sides, α the included angle, and u the third side. The given data are

$$(4) \quad x = 63, \quad y = 78, \quad \alpha = 60^\circ = \frac{\pi}{3}, \quad dx = dy = 0.1, \quad d\alpha = 0.01745 \text{ (radian)}.$$

Differentiating (3), we get

$$\frac{\partial u}{\partial x} = \frac{x - y \cos \alpha}{u}, \quad \frac{\partial u}{\partial y} = \frac{y - x \cos \alpha}{u}, \quad \frac{\partial u}{\partial \alpha} = \frac{xy \sin \alpha}{u}.$$

Hence, using (C),

$$du = \frac{(x - y \cos \alpha)dx + (y - x \cos \alpha)dy + xy \sin \alpha \, d\alpha}{u}.$$

Substituting the values from (4), we find

$$du = \frac{2.4 + 4.65 + 74.25}{71.7} = 1.13 \text{ ft.} \quad \text{Ans.}$$

The percentage error = $100 \frac{du}{u} = 1.6\%$. *Ans.*

PROBLEMS

1. The legs of a right triangle measured 6 ft. and 8 ft. respectively, with maximum errors in each of 0.1 ft. Find approximately the maximum error and percentage error in calculating (a) the area, (b) the hypotenuse, from these measurements. *Ans.* (a) 0.7 sq. ft., 2.9%; (b) 0.14 ft., 1.4%.

2. In the preceding problem find the approximate error in calculating the angle opposite the longer side from the given dimensions, and the approximate maximum error in that angle in radians and degrees.

3. The radii of the bases of a frustum of a right circular cone measure 5 in. and 11 in. respectively, and the slant height measures 12 in. The maximum error in each measurement is 0.1 in. Find the approximate error and percentage error in calculating from these measurements (a) the altitude; (b) the volume (see (12), Art. 1).

Ans. (a) 0.23 in., 2.2%; (b) 32π cu. in., $4\frac{1}{2}\%$.

4. One side of a triangle measures 2000 ft., and the adjacent angles measure 30° and 60° respectively, with a maximum error in each angle of $30'$. The maximum error in the measurement of the side is ± 1 ft. Find the approximate maximum error and percentage error in calculating from these measurements (a) the altitude on the given side; (b) the area of the triangle. *Ans.* (a) 17.88 ft., 2.1 %.

5. The diameter and altitude of a right circular cylinder are found by measurement to be 12 in. and 8 in. respectively. If there is a probable error of 0.2 in. in each measurement, what is approximately the greatest possible error in the computed volume? *Ans.* 16.8π cu. in.

6. The dimensions of a box are found by measurement to be 6 ft., 8 ft., 12 ft. If there is a probable error of 0.05 ft., (a) what is approximately the greatest possible error in the computed volume? (b) What is the percentage error? *Ans.* (a) 10.8 cu. ft.; (b) $\frac{1}{8}\%$.

7. Given the surface $z = \frac{x-y}{x+y}$. If, at the point where $x = 4$, $y = 2$, x and y are each increased by $\frac{1}{10}$, what is the approximate change in z ? *Ans.* $-\frac{1}{80}$.

8. The specific gravity of a solid is given by the formula $s = \frac{P}{w}$, where P is the weight in a vacuum and w is the weight of an equal volume of water. How is the computed specific gravity affected by an error of $\pm \frac{1}{10}$ in weighing P and $\pm \frac{1}{6}$ in weighing w , assuming $P = 8$ and $w = 1$ in the experiment, (a) if both errors are positive? (b) if one error is negative? (c) What is approximately the largest percentage error? *Ans.* (a) 0.3; (b) 0.5; (c) $6\frac{1}{4}\%$.

9. The diameter and slant height of a right circular cone are found by measurement to be 10 in. and 20 in. respectively. If there is a probable error of 0.2 in. in each measurement, what approximately is the greatest possible error in the computed value of (a) the volume? (b) the curved surface? *Ans.* (a) $\frac{37 \pi \sqrt{15}}{18} = 25$ cu. in.; (b) $3 \pi = 9.42$ sq. in.

10. Two sides of a triangle are found by measurement to be 63 ft. and 78 ft. and the included angle to be 60° . If there is a probable error of 0.5 ft. in measuring the sides and of $2''$ in measuring the angle, what is approximately the greatest possible error in the computed value of the area? (See (7), Art. 2.) *Ans.* 73.6 sq. ft.

11. If specific gravity is determined by the formula $s = \frac{A}{A - W}$, where A is the weight in air and W the weight in water, what is (a) approximately the largest error in s if A can be read within 0.01 lb. and W within 0.02 lb., the actual readings being $A = 9$ lb., $W = 5$ lb.? (b) the largest relative error? *Ans.* (a) 0.0144; (b) $\frac{2}{3885}\%$.

12. The resistance of a circuit was found by using the formula $C = \frac{E}{R}$, where C = current and E = electromotive force. If there is an error of $\frac{1}{10}$ ampere in reading C and $\frac{1}{20}$ volt in reading E , (a) what is the approximate error in R if the readings are $C = 15$ amperes and $E = 110$ volts? (b) What is the percentage error? *Ans.* (a) 0.0522 ohms; (b) $\frac{17}{66}\%$.

13. If the formula $\sin(x + y) = \sin x \cos y + \cos x \sin y$ were used to calculate $\sin(x + y)$, what approximate error would result if an error of 0.1° were made in measuring both x and y , the measurements of the two acute angles giving $\sin x = \frac{3}{5}$ and $\sin y = \frac{5}{13}$? *Ans.* 0.0018.

14. The acceleration of a particle down an inclined plane is given by $a = g \sin i$. If g varies by 0.1 ft. per second per second, and i , which is measured as 30° , may be in error 1° , what is the approximate error in the computed value of a ? Take the normal value of g to be 32 ft. per second per second. *Ans.* 0.534 ft. per second per second.

15. The period of a pendulum is $P = 2\pi\sqrt{\frac{l}{g}}$. (a) What is the greatest approximate error in the period if there is an error of ± 0.1 ft. in measuring a 10-foot suspension and g , taken as 32 ft. per second per second, may be in error by 0.05 ft. per second per second? (b) What is the percentage error? *Ans.* (a) 0.0204 sec.; (b) $\frac{37}{24}\%$.

16. The dimensions of a cone are radius of base = 4 in., altitude = 6 in. What is the approximate error in volume and in total surface if there is a shortage of 0.01 in. per inch in the measure used?

Ans. $dV = 3.0159$ cu. in.; $dS = 2.818$ sq. in.

17. The length l and the period P of a simple pendulum are connected by the equation $4\pi^2 l = P^2 g$. If l is calculated assuming $P = 1$ sec. and $g = 32$ ft. per second per second, what is approximately the error in l if the true values are $P = 1.02$ sec. and $g = 32.01$ ft. per second per second? What is the percentage error?

18. A solid is in the form of a cylinder capped at each end with a hemisphere of the same radius as the cylinder. Its measured dimensions are diameter = 8 in. and total length = 20 in. What is approximately the error in volume and surface if the tape used in measuring has stretched uniformly $\frac{1}{2}\%$ beyond its proper length?

19. Assuming the characteristic equation of a perfect gas to be $vp = Rt$, where v = volume, p = pressure, t = absolute temperature, and R a constant, what is the relation between the differentials dv , dp , dt ?

Ans. $v dp + p dv = R dt$.

20. Using the result in the last example as applied to air, suppose that in a given case we have found by actual experiment that $t = 300^\circ \text{C.}$, $p = 2000$ lb. per square foot, $v = 14.4$ cu. ft. Find the change in p , assuming it to be uniform, when t changes to 301°C. , and v to 14.5 cu. ft. $R = 96$.

Ans. -7.22 lb. per square foot.

229. Total derivatives. Rates. Turn now to the case where x and y in

$$(1) \quad u = f(x, y)$$

are not independent variables. Assume, for example, that both are functions of a third variable t , namely,

$$(2) \quad x = \phi(t), \quad y = \psi(t).$$

When these values are substituted in (1), u becomes a function of one variable t , and its derivative may be found in the usual manner. We now have

$$(3) \quad du = \frac{du}{dt} dt, \quad dx = \frac{dx}{dt} dt, \quad dy = \frac{dy}{dt} dt.$$

Formula (B) was established with the assumption that x and y were independent variables. We may easily show that it holds also in the present case. To this end, return to (10), Art. 227, and divide both members by Δt . Changing the notation, this may be written

$$(4) \quad \frac{\Delta u}{\Delta t} = \frac{\partial u}{\partial x} \frac{\Delta x}{\Delta t} + \frac{\partial u}{\partial y} \frac{\Delta y}{\Delta t} + \left(\epsilon \frac{\Delta x}{\Delta t} + \epsilon' \frac{\Delta y}{\Delta t} \right).$$

Now when $\Delta t \rightarrow 0$, $\Delta x \rightarrow 0$ and $\Delta y \rightarrow 0$. Hence (see Art. 227)

$$\lim_{\Delta t \rightarrow 0} \epsilon = 0, \quad \lim_{\Delta t \rightarrow 0} \epsilon' = 0.$$

Therefore, when $\Delta t \rightarrow 0$, (4) becomes

$$(D) \quad \frac{du}{dt} = \frac{\partial u}{\partial x} \frac{dx}{dt} + \frac{\partial u}{\partial y} \frac{dy}{dt}.$$

Multiplying both members by dt and using (3), we obtain (B). That is, (B) holds also when x and y are functions of a third variable t .

In the same way, if

$$u = f(x, y, z),$$

and x, y, z are all functions of t , we get

$$(E) \quad \frac{du}{dt} = \frac{\partial u}{\partial x} \frac{dx}{dt} + \frac{\partial u}{\partial y} \frac{dy}{dt} + \frac{\partial u}{\partial z} \frac{dz}{dt},$$

and so on for any number of variables.

In (D) we may suppose $t = x$; then y is a function of x , and u is really a function of the one variable x , giving

$$(F) \quad \frac{du}{dx} = \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \frac{dy}{dx}.$$

In the same way, from (E) we have, when y and z are functions of x ,

$$(G) \quad \frac{du}{dx} = \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \frac{dy}{dx} + \frac{\partial u}{\partial z} \frac{dz}{dx}.$$

The student should observe that $\frac{\partial u}{\partial x}$ and $\frac{du}{dx}$ have quite different meanings. The partial derivative $\frac{\partial u}{\partial x}$ is formed on the supposition that the *particular variable x alone varies*, all other variables being held fast. But

$$\frac{du}{dx} = \lim_{\Delta x \rightarrow 0} \left(\frac{\Delta u}{\Delta x} \right),$$

where Δu is the *total increment of u* due to changes in *all the variables* caused by the change Δx in the independent variable. In contradistinction to partial derivatives, $\frac{du}{dt}$, $\frac{du}{dx}$ are called *total derivatives* with respect to t and x respectively.

It should be observed that $\frac{\partial u}{\partial x}$ has a perfectly definite value for any point (x, y) , while $\frac{du}{dx}$ depends not only on the point (x, y) but also on the particular direction chosen to reach that point.

ILLUSTRATIVE EXAMPLE 1. Given $u = \sin \frac{x}{y}$, $x = e^t$, $y = t^2$; find $\frac{du}{dt}$.

Solution. $\frac{\partial u}{\partial x} = \frac{1}{y} \cos \frac{x}{y}$, $\frac{\partial u}{\partial y} = -\frac{x}{y^2} \cos \frac{x}{y}$; $\frac{dx}{dt} = e^t$, $\frac{dy}{dt} = 2t$.

Substituting in (D), $\frac{du}{dt} = (t-2) \frac{e^t}{t^3} \cos \frac{e^t}{t^2}$. *Ans.*

ILLUSTRATIVE EXAMPLE 2. Given $u = e^{ax}(y-z)$, $y = a \sin x$, $z = \cos x$; find $\frac{du}{dx}$.

Solution. $\frac{\partial u}{\partial x} = ae^{ax}(y-z)$, $\frac{\partial u}{\partial y} = e^{ax}$, $\frac{\partial u}{\partial z} = -e^{ax}$; $\frac{dy}{dx} = a \cos x$, $\frac{dz}{dx} = -\sin x$.

Substituting in (G),

$$\frac{du}{dx} = ae^{ax}(y-z) + ae^{ax} \cos x - e^{ax} \sin x = e^{ax}(a^2 + 1) \sin x. \quad \text{Ans.}$$

NOTE. In examples like the above, u could, by substitution, be found explicitly in terms of the independent variable and then differentiated directly; but generally this process would be longer and in many cases could not be used at all.

Formulas (D) and (E) are useful in all applications involving time-rates of change of functions of two or more variables. The process is practically the same as that outlined in the rule given in Art. 52, except that, instead of differentiating with respect to t (Third Step), we find the partial derivatives and substitute in (D) or (E). Let us illustrate by an example.

ILLUSTRATIVE EXAMPLE 3. The altitude of a circular cone is 100 in., and decreases at the rate of 10 in. per second; and the radius of the base is 50 in., and increases at the rate of 5 in. per second. At what rate is the volume changing?

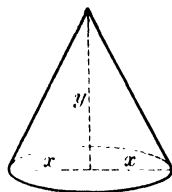
Solution. Let x = radius of base, y = altitude; then

$$u = \frac{1}{3} \pi x^2 y = \text{volume}, \quad \frac{\partial u}{\partial x} = \frac{2}{3} \pi x y, \quad \frac{\partial u}{\partial y} = \frac{1}{3} \pi x^2.$$

$$\text{Substituting in (D),} \quad \frac{du}{dt} = \frac{2}{3} \pi x y \frac{dx}{dt} + \frac{1}{3} \pi x^2 \frac{dy}{dt}.$$

$$\text{But} \quad x = 50, \quad y = 100, \quad \frac{dx}{dt} = 5, \quad \frac{dy}{dt} = -10.$$

$$\therefore \frac{du}{dt} = \frac{2}{3} \pi \cdot 5000 \cdot 5 - \frac{1}{3} \pi \cdot 2500 \cdot 10 = 15.15 \text{ cu. ft. per second, increasing.} \quad \text{Ans.}$$



230. Change of variables. If the variables in

$$(1) \quad u = f(x, y)$$

are changed by the transformation

$$(2) \quad x = \phi(r, s), \quad y = \psi(r, s),$$

the partial derivatives of u with respect to the new variables r and s can be obtained by (D). For, if we hold s fast, then x and y in (2) are functions of r only. Hence we have

$$(3) \quad \frac{\partial u}{\partial r} = \frac{\partial u}{\partial x} \frac{\partial x}{\partial r} + \frac{\partial u}{\partial y} \frac{\partial y}{\partial r},$$

all derivatives with respect to r now being partial.

In the same way,

$$(4) \quad \frac{\partial u}{\partial s} = \frac{\partial u}{\partial x} \frac{\partial x}{\partial s} + \frac{\partial u}{\partial y} \frac{\partial y}{\partial s}.$$

In particular, let the transformation be

$$(5) \quad x = x' + h, \quad y = y' + k,$$

the new variables being x' and y' , and h, k being constants. Then

$$\frac{\partial x}{\partial x'} = 1, \quad \frac{\partial x}{\partial y'} = 0, \quad \frac{\partial y}{\partial x'} = 0, \quad \frac{\partial y}{\partial y'} = 1.$$

Then we obtain, from (3) and (4),

$$(6) \quad \frac{\partial u}{\partial x} = \frac{\partial u}{\partial x'}, \quad \frac{\partial u}{\partial y} = \frac{\partial u}{\partial y'}.$$

Hence the transformation (5) leaves the value of the partial derivatives unchanged.

If the values of x and y in (5) are substituted in (1), the result is

$$(7) \quad u = f(x, y) = F(x', y').$$

The results in (6) may now be written

$$(8) \quad f_x(x, y) = F_x(x', y'), \quad f_y(x, y) = F_y(x', y').$$

In Art. 229 it was shown that (B) is true when x and y are functions of a single independent variable t . We prove now that (B) holds also when x and y are functions of two independent variables r, s , as in (2). For by (B), when r and s are the independent variables, we have

$$dx = \frac{\partial x}{\partial r} dr + \frac{\partial x}{\partial s} ds, \quad dy = \frac{\partial y}{\partial r} dr + \frac{\partial y}{\partial s} ds.$$

Substitute these values in the expression

$$(9) \quad \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial y} dy$$

and reduce by (3) and (4). The result is

$$(10) \quad \frac{\partial u}{\partial r} dr + \frac{\partial u}{\partial s} ds.$$

But, by (1) and (2), u becomes a function of the independent variables r and s . Then, by (B), (10) equals du . Hence (9) also equals du .

Therefore (B) holds when x and y are functions of one or of two independent variables. In the same way, it can be shown that (C) holds when x, y, z are functions of one, two, or three independent variables.

231. Differentiation of implicit functions. The equation

$$(1) \quad f(x, y) = 0$$

defines either x or y as an implicit function of the other. It represents an equation containing x and y when all its terms have been transposed to the first member. Let

$$(2) \quad u = f(x, y);$$

then

$$\frac{du}{dx} = \frac{\partial f}{\partial x} + \frac{\partial f}{\partial y} \frac{dy}{dx}, \quad \text{by (F)}$$

and y is an arbitrary function of x . Now let y be the function of x satisfying (1). Then $u = 0$ and $du = 0$, and hence

$$(3) \quad \frac{\partial f}{\partial x} + \frac{\partial f}{\partial y} \frac{dy}{dx} = 0.$$

Solving, we get

$$(H) \quad \frac{dy}{dx} = - \frac{\frac{\partial f}{\partial x}}{\frac{\partial f}{\partial y}}. \quad \left(\frac{\partial f}{\partial y} \neq 0 \right)$$

Thus we have a formula for differentiating implicit functions. This formula in the form (3) is equivalent to the process employed in Art. 41 for differentiating implicit functions, and all the examples on pages 40 and 41 may be solved by it.

When the equation of a curve is in the form (1), formula (H) affords an easy way of getting the slope.

ILLUSTRATIVE EXAMPLE 1. Given $x^2y^4 + \sin y = 0$, find $\frac{dy}{dx}$.

Solution. Let $f(x, y) = x^2y^4 + \sin y$.

$$\frac{\partial f}{\partial x} = 2xy^4, \quad \frac{\partial f}{\partial y} = 4x^2y^3 + \cos y.$$

Therefore, from (H), $\frac{dy}{dx} = -\frac{2xy^4}{4x^2y^3 + \cos y}$. *Ans.*

ILLUSTRATIVE EXAMPLE 2. If x increases at the rate of 2 in. per second as it passes through the value $x = 3$ in., at what rate must y change when $y = 1$ in., in order that the function $2xy^2 - 3x^2y$ shall remain constant?

Solution. Let $u = 2xy^2 - 3x^2y$; then, since u remains constant, $\frac{du}{dt} = 0$. Substituting this value in the left-hand member of (D), transposing, and solving for $\frac{dy}{dt}$, we get

$$(4) \quad \frac{dy}{dt} = -\frac{\frac{\partial u}{\partial x} \frac{dx}{dt}}{\frac{\partial u}{\partial y}}.$$

Also,
$$\frac{\partial u}{\partial x} = 2y^2 - 6xy, \quad \frac{\partial u}{\partial y} = 4xy - 3x^2.$$

Now, substituting in (4),
$$\frac{dy}{dt} = -\frac{2y^2 - 6xy}{4xy - 3x^2} \frac{dx}{dt}.$$

But
$$x = 3, \quad y = 1, \quad \frac{dx}{dt} = 2.$$

Therefore,
$$\frac{dy}{dt} = -2\frac{2}{15} \text{ in. per second. } \textit{Ans.}$$

In like manner, the equation

$$(5) \quad F(x, y, z) = 0$$

defines z as an implicit function of the two independent variables x and y . To find the partial derivatives of z with respect to x and to y , proceed as follows.

Let
$$u = f(x, y, z).$$

Then
$$du = \frac{\partial F}{\partial x} dx + \frac{\partial F}{\partial y} dy + \frac{\partial F}{\partial z} dz,$$

by (B), and this holds no matter what the independent variables are (Art. 230). Now let z be chosen as that function of the independent

variables x and y which satisfies (5). Then $u = 0$, $du = 0$, and we have

$$(6) \quad \frac{\partial F}{\partial x} dx + \frac{\partial F}{\partial y} dy + \frac{\partial F}{\partial z} dz = 0.$$

But now $dz = \frac{\partial z}{\partial x} dx + \frac{\partial z}{\partial y} dy.$ By (B)

Substituting this value in (6) and simplifying gives

$$\left(\frac{\partial F}{\partial x} + \frac{\partial F}{\partial z} \frac{\partial z}{\partial x} \right) dx + \left(\frac{\partial F}{\partial y} + \frac{\partial F}{\partial z} \frac{\partial z}{\partial y} \right) dy = 0.$$

Here $dx (= \Delta x)$ and $dy (= \Delta y)$ are independent increments. We may therefore set $dy = 0$, $dx \neq 0$, divide through by dx , and solve for $\frac{\partial z}{\partial x}$. The result is

$$(I) \quad \frac{\partial z}{\partial x} = - \frac{\frac{\partial F}{\partial x}}{\frac{\partial F}{\partial z}}.$$

Proceeding in a similar manner, we may prove

$$(J) \quad \frac{\partial z}{\partial y} = - \frac{\frac{\partial F}{\partial y}}{\frac{\partial F}{\partial z}}.$$

Formulas (I) and (J) are to be interpreted as follows: In the left-hand members z is the function of x and y satisfying (5). In the right-hand members F is the function of three variables, x, y, z , given in the left-hand member of (5).

The generalization of (H), (I), (J) to an implicit function u of any number of variables is now obvious.

ILLUSTRATIVE EXAMPLE. By the equation

$$\frac{x^2}{24} + \frac{y^2}{12} + \frac{z^2}{6} - 1 = 0,$$

z is defined as an implicit function of x and y . Find the partial derivatives of this function.

Solution. $F = \frac{x^2}{24} + \frac{y^2}{12} + \frac{z^2}{6} - 1.$

Hence $\frac{\partial F}{\partial x} = \frac{x}{12}, \quad \frac{\partial F}{\partial y} = \frac{y}{6}, \quad \frac{\partial F}{\partial z} = \frac{z}{3}.$

Substituting in (I) and (J), we get

$$\frac{\partial z}{\partial x} = - \frac{x}{4z}, \quad \frac{\partial z}{\partial y} = - \frac{y}{2z}. \quad \text{Ans.}$$

(Compare with the Illustrative Example in Art. 226.)

PROBLEMS

In Problems 1–5 find $\frac{du}{dt}$.

1. $u = x^2 - 3xy + 2y^2$; $x = \cos t$, $y = \sin t$.

Ans. $\frac{du}{dt} = \sin 2t - 3 \cos 2t$.

2. $u = x + 4\sqrt{xy} - 3y$; $x = t^3$, $y = \frac{1}{t}$.

$\frac{du}{dt} = 3t^2 + 4 + \frac{3}{t^2}$.

3. $u = e^x \sin y + e^y \sin x$; $x = \frac{1}{2}t$, $y = 2t$.

Ans. $\frac{du}{dt} = e^{\frac{1}{2}t}(\frac{1}{2} \sin 2t + 2 \cos 2t) + e^{2t}(2 \sin \frac{1}{2}t + \frac{1}{2} \cos \frac{1}{2}t)$.

4. $u = 2x^2 - xy + y^2$; $x = \cos 2t$, $y = \sin t$.

5. $u = xyz + yz + zx$; $x = \frac{1}{t}$, $y = e^t$, $z = e^{-t}$.

In Problems 6–10 find $\frac{dy}{dx}$ by formula (H).

6. $Ax^2 + 2Bxy + Cy^2 + 2Dx + 2Ey + F = 0$.

Ans. $\frac{dy}{dx} = -\frac{Ax + By + D}{Bx + Cy + E}$.

7. $x^3 + y^3 - 3axy = 0$.

$\frac{dy}{dx} = \frac{ay - x^2}{y^2 - ax}$.

8. $e^x \sin y - e^y \cos x = 1$.

$\frac{dy}{dx} = \frac{e^y \sin x + e^x \sin y}{e^y \cos x - e^x \cos y}$.

9. $x^4 - x^2y^2 - x^2 + 2y^2 = 8$.

10. $Ax^4 + 2Bx^2y^2 + Cy^4 = (x^2 + y^2)^2$.

In Problems 11–15 verify that the given values of x and y satisfy the equation, and find the corresponding value of $\frac{dy}{dx}$.

11. $x^2 + 2xy + 2y = 22$; $x = 2$, $y = 3$.

Ans. $\frac{dy}{dx} = -\frac{5}{3}$.

12. $x^3 - y^3 + 4xy = 0$; $x = 2$, $y = -2$.

$\frac{dy}{dx} = 1$.

13. $Ax + By + Ce^{xy} = C$; $x = 0$, $y = 0$.

$\frac{dy}{dx} = -\frac{A}{B}$.

14. $2x - \sqrt{2xy} + y = 4$; $x = 2$, $y = 4$.

15. $e^x \cos y + e^y \sin x = 1$; $x = 0$, $y = 0$.

In Problems 16–20 find $\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial y}$.

16. $Ax^2 + By^2 + Cz^2 = D$. Ans. $\frac{\partial z}{\partial x} = -\frac{Ax}{Cz}$; $\frac{\partial z}{\partial y} = -\frac{By}{Cz}$.

17. $Axy + Byz + Czx = D$. $\frac{\partial z}{\partial x} = -\frac{Ay + Cz}{Cx + By}$; $\frac{\partial z}{\partial y} = -\frac{Ax + Cz}{Cx + By}$.

$$18. x + 2y + z - 2\sqrt{xyz} = 10. \text{ Ans. } \frac{\partial z}{\partial x} = \frac{yz - \sqrt{xyz}}{\sqrt{xyz} - xy}; \frac{\partial z}{\partial y} = \frac{xz - 2\sqrt{xyz}}{\sqrt{xyz} - xy}.$$

$$19. x^3 + y^3 + z^3 - 3xyz = 0.$$

$$20. Ax^2 + By^2 + Cz^2 + 2Dxy + 2Eyz + 2Fzr = G.$$

21. A point is moving on the curve of intersection of the sphere $x^2 + y^2 + z^2 = 49$ and the plane $y = 2$. When x is 6 and is increasing 4 units per second, find (a) the rate at which z is changing and (b) the speed with which the point is moving.

Ans. (a) 8 units per second; (b) $4\sqrt{5}$ units per second.

22. A point is moving on the curve of intersection of the surface $x^2 + xy + y^2 - z^2 = 0$ and the plane $x - y + 2 = 0$. When x is 3 and is increasing 2 units per second, find (a) the rate at which y is changing, (b) the rate at which z is changing, (c) the speed with which the point is moving.

Ans. (a) 2 units per second; (b) $\frac{2}{7}$ units per second; (c) 4.44 units per second.

23. The characteristic equation of a perfect gas is $R\theta = pr$, where θ is the temperature, p the pressure, r the volume, and R a constant. At a certain instant a given amount of gas has a volume of 15 cu. ft. and is under a pressure of 25 lb. per square inch. Assuming $R = 96$, find the temperature and the rate at which the temperature is changing if the volume is increasing at the rate of $\frac{1}{2}$ cu. ft. per second and the pressure is decreasing at the rate of $\frac{1}{10}$ lb. per square inch per second.

Ans. Temperature is increasing at the rate of $\frac{1}{6}$ degrees per second.

24. A triangle ABC is being transformed so that the angle A changes at a uniform rate from 0° to 90° in 10 sec., while side AC decreases 1 in. per second and side AB increases 1 in. per second. If at the time of observation $A = 60^\circ$, $AC = 16$ in., and $AB = 10$ in., (a) how fast is BC changing? (b) how fast is the area of ABC changing?

Ans. (a) 0.911 in. per second; (b) 8.88 sq. in. per second.

232. Derivatives of higher order. If

$$(1) \quad u = f(x, y),$$

then

$$(2) \quad \frac{\partial u}{\partial x} = f_x(x, y), \quad \frac{\partial u}{\partial y} = f_y(x, y)$$

are themselves functions of x and y , and can, in turn, be differentiated. Thus, taking the first function and differentiating, we have,

$$(3) \quad \frac{\partial^2 u}{\partial x^2} = f_{xx}(x, y), \quad \frac{\partial^2 u}{\partial y \partial x} = f_{yx}(x, y).$$

In the same manner, from the second function in (2), we obtain

$$(4) \quad \frac{\partial^2 u}{\partial x \partial y} = f_{xy}(x, y), \quad \frac{\partial^2 u}{\partial y^2} = f_{yy}(x, y).$$

In (3) and (4) there are apparently four derivatives of the second order. It is shown below that

$$(K) \quad \frac{\partial^2 u}{\partial y \partial x} = \frac{\partial^2 u}{\partial x \partial y},$$

provided, merely, that the derivatives concerned are continuous. That is, *the order of differentiating successively with respect to x and y is immaterial*. Thus $f(x, y)$ has only three partial derivatives of the second order, namely,

$$(5) \quad f_{xx}(x, y), \quad f_{xy}(x, y) = f_{yx}(x, y), \quad f_{yy}(x, y).$$

This may be easily extended to higher derivatives. For instance, since (K) is true,

$$\frac{\partial^3 u}{\partial x^2 \partial y} = \frac{\partial}{\partial x} \left(\frac{\partial^2 u}{\partial x \partial y} \right) = \frac{\partial^3 u}{\partial x \partial y \partial x} = \frac{\partial^2}{\partial x \partial y} \left(\frac{\partial u}{\partial x} \right) = \frac{\partial^2}{\partial y \partial x} \left(\frac{\partial u}{\partial x} \right) = \frac{\partial^3 u}{\partial y \partial x^2}.$$

Similar results hold for functions of three or more variables.

ILLUSTRATIVE EXAMPLE. Given $u = x^4 y - 3 x^2 y^3$; verify $\frac{\partial^2 u}{\partial y \partial x} = \frac{\partial^2 u}{\partial x \partial y}$.

$$\begin{aligned} \text{Solution.} \quad \frac{\partial u}{\partial x} &= 4 x^3 y - 6 x y^3, & \frac{\partial^2 u}{\partial y \partial x} &= 4 x^3 - 18 x y^2, \\ \frac{\partial u}{\partial y} &= x^4 - 9 x^2 y^2, & \frac{\partial^2 u}{\partial x \partial y} &= 4 x^3 - 18 x y^2. \end{aligned}$$

Hence the formula is verified.

Proof of (K). Consider the expression

$$(6) \quad F = f(x + \Delta x, y + \Delta y) - f(x + \Delta x, y) - f(x, y + \Delta y) + f(x, y).$$

Introduce the function

$$(7) \quad \phi(u) = f(u, y + \Delta y) - f(u, y),$$

where u is an auxiliary variable. Then

$$\begin{aligned} \phi(x + \Delta x) &= f(x + \Delta x, y + \Delta y) - f(x + \Delta x, y), \\ (8) \quad \phi(x) &= f(x, y + \Delta y) - f(x, y). \end{aligned}$$

Hence (6) may be written

$$(9) \quad F = \phi(x + \Delta x) - \phi(x).$$

Applying the Theorem of Mean Value (D), Art. 116,

$$\begin{aligned} (10) \quad F &= \Delta x \phi'(x + \theta_1 \Delta x). & (0 < \theta_1 < 1) \\ &[f(x) = \phi(u), a = x, \Delta a = \Delta x.] \end{aligned}$$

The value of $\phi'(x + \theta_1 \Delta x)$ is obtained from (8) by taking the partial derivative with respect to x and replacing x by $x + \theta_1 \Delta x$. Thus (10) becomes

$$(11) \quad F = \Delta x (f_x(x + \theta_1 \Delta x, y + \Delta y) - f_x(x + \theta_1 \Delta x, y)).$$

Now apply (D), Art. 116, to $f_x(x + \theta_1 \Delta x, v)$, regarding v as the independent variable. Then

$$(12) \quad F = \Delta x \Delta y f_{xy}(x + \theta_1 \Delta x, y + \theta_2 \Delta y). \quad (0 < \theta_2 < 1)$$

If the second and third terms of the right-hand member of (6) are interchanged, a similar procedure will give

$$(13) \quad F = \Delta y \Delta x f_{yx}(x + \theta_3 \Delta x, y + \theta_4 \Delta y). \quad (0 < \theta_3 < 1, 0 < \theta_4 < 1)$$

Hence from (12) and (13),

$$(14) \quad f_{yx}(x + \theta_1 \Delta x, y + \theta_2 \Delta y) = f_{xy}(x + \theta_3 \Delta x, y + \theta_4 \Delta y).$$

Taking the limit of both sides as Δx and Δy approach zero as limits, we have

$$(15) \quad f_{yx}(x, y) = f_{xy}(x, y),$$

since these functions are assumed to be continuous.

PROBLEMS

Find the second partial derivatives of each of the following functions.

1. $f(x, y) = Ax^2 + 2Bxy + Cy^2$.

Ans. $f_{xx}(x, y) = 2A$; $f_{xy}(x, y) = 2B$; $f_{yy}(x, y) = 2C$.

2. $f(x, y) = Ax^3 + Bx^2y + Cxy^2 + Dy^3$.

Ans. $f_{xx}(x, y) = 6Ax + 2By$; $f_{xy}(x, y) = 2Bx + 2Cy$; $f_{yy}(x, y) = 2Cx + 6Dy$.

3. $f(x, y) = Ax + By + Ce^{xy}$.

Ans. $f_{xx}(x, y) = Cy^2e^{xy}$; $f_{xy} = C(1 + xy)e^{xy}$; $f_{yy}(x, y) = Cx^2e^{xy}$.

4. $f(x, y) = \frac{Ax + By}{Cx + Dy}$.

5. $f(x, y) = x^2 \cos y + y^2 \sin x$.

6. If $f(x, y) = x^3 + 3x^2y + 6xy^2 - y^3$, show that

$$f_{xx}(2, 3) = 30, f_{xy}(2, 3) = 48, f_{yy}(2, 3) = 6.$$

7. If $f(x, y) = x^4 - 4x^3y + 8xy^3 - y^4$, show that

$$f_{xx}(2, -1) = 96, f_{xy}(2, -1) = -24, f_{yy}(2, -1) = -108.$$

8. If $f(x, y) = 2x^4 - 3x^2y^2 + y^4$, find the values of

$$f_{xx}(2, -2), f_{xy}(2, -2), f_{yy}(2, -2).$$

9. If $u = Ax^4 + Bx^3y + Cx^2y^2 + Dxy^3 + Ey^4$, verify the following results.

$$\frac{\partial^3 u}{\partial x^3} = 24 Ax + 6 By, \quad \frac{\partial^3 u}{\partial x^2 \partial y} = 6 Bx + 4 Cy,$$

$$\frac{\partial^3 u}{\partial x \partial y^2} = 4 Cx + 6 Dy, \quad \frac{\partial^3 u}{\partial y^3} = 6 Dx + 24 Ey.$$

10. If $u = (ax^2 + by^2 + cz^2)^3$, show that $\frac{\partial^3 u}{\partial x^2 \partial y} = \frac{\partial^3 u}{\partial x \partial y \partial x} = \frac{\partial^3 u}{\partial y \partial x^2}.$

11. If $u = \frac{xy}{x+y}$, show that $x^2 \frac{\partial^2 u}{\partial x^2} + 2xy \frac{\partial^2 u}{\partial x \partial y} + y^2 \frac{\partial^2 u}{\partial y^2} = 0.$

12. If $u = \ln \sqrt{x^2 + y^2}$, show that $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0.$

13. If $u = \frac{1}{\sqrt{x^2 + y^2 + z^2}}$, show that $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0.$

ADDITIONAL PROBLEMS

1. A circular hill has a central vertical section in the form of the curve whose equation is $x^2 + 160y - 1600 = 0$, where the unit is 1 yd. The top is being cut down in horizontal layers at the constant rate of 100 cu. yd. per day. How fast is the area of the horizontal cross section increasing when the top has been cut down a vertical distance of 4 yd.?

Ans. 25 sq. yd. per day.

2. If $u = \frac{e^{xy}}{e^x + e^y}$, show that $\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = (x + y - 1)u.$

3. If $u = \frac{1}{r}$, where $r = \sqrt{x^2 + y^2 + z^2}$, show that
$$\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2 = \frac{1}{r^4}.$$

4. If $z = x^2 \arctan \frac{y}{x} - y^2 \arctan \frac{x}{y}$, show that $\frac{\partial^2 z}{\partial x \partial y} = \frac{x^2 - y^2}{x^2 + y^2}.$

5. If $u = z \arctan \frac{x}{y}$, show that $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0.$

6. If $u = \ln(e^x + e^y + e^z)$, show that $\frac{\partial^3 u}{\partial x \partial y \partial z} = 2e^{x+y+z-3u}.$

7. If $u = f(x, y)$ and $x = r \cos \theta$, $y = r \sin \theta$, show that

$$\frac{\partial u}{\partial x} = \cos \theta \frac{\partial u}{\partial r} - \frac{\sin \theta}{r} \frac{\partial u}{\partial \theta},$$

$$\frac{\partial u}{\partial y} = \sin \theta \frac{\partial u}{\partial r} + \frac{\cos \theta}{r} \frac{\partial u}{\partial \theta}.$$

8. Let $u = (x_1^2 + x_2^2 + \cdots + x_n^2)^k$. What values of k will satisfy the equation $\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2} + \cdots + \frac{\partial^2 u}{\partial x_n^2} = 0$? Ans. $k = 1 - \frac{n}{2}$ ($n > 2$).

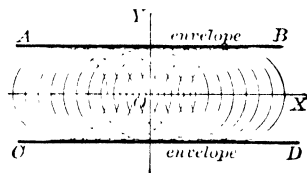
CHAPTER XXIV

APPLICATIONS OF PARTIAL DERIVATIVES

233. Envelope of a family of curves. The equation of a curve generally involves, besides the variables x and y , certain constants upon which the size, shape, and position of that particular curve depend. For example, the locus of the equation

$$(x - \alpha)^2 + y^2 = r^2$$

is a circle whose center lies on the x -axis at a distance of α from the origin, its size depending on the radius r . Suppose α to take on a series of values while r is held fast; then we shall have a corresponding series of circles of equal radius differing in their distances from the origin, as shown in the figure.



Any system of curves formed in this way is called a *family of curves*, and the quantity α , which is constant for any one curve, but changes in passing from one curve to another, is called a *variable parameter*. To indicate that α enters as a variable parameter it is usual to insert it in the functional symbol, thus:

$$f(x, y, \alpha) = 0.$$

The curves of a family may be tangent to the same curve or group of curves, as in the above figure. In that case the name *envelope* of the family is applied to the curve or group of curves. We shall now explain a method for finding the equation of the envelope of a family of curves. Suppose that the curve whose parametric equations are

$$(1) \quad x = \phi(\alpha), \quad y = \psi(\alpha)$$

is tangent to each curve of the family

$$(2) \quad f(x, y, \alpha) = 0,$$

the parameter α being the same in both cases. For any common value of α equations (1) will satisfy (2). Hence, by (E), Art. 229, since $u = f(x, y, \alpha)$, $du = df = 0$, and z is replaced by α , we have

$$(3) \quad f_x(x, y, \alpha)\phi'(\alpha) + f_y(x, y, \alpha)\psi'(\alpha) + f_\alpha(x, y, \alpha) = 0.$$

The slope of (1) at any point is

$$(4) \quad \frac{dy}{dx} = \frac{\psi'(\alpha)}{\phi'(\alpha)}, \quad (A), \text{ Art. 81}$$

and the slope of (2) at any point is

$$(5) \quad \frac{dy}{dx} = -\frac{f_x(x, y, \alpha)}{f_y(x, y, \alpha)}. \quad (H), \text{ Art. 231}$$

Hence if the curves (1) and (2) are tangent, the slopes at a point of tangency will be equal, giving

$$(6) \quad \frac{\psi'(\alpha)}{\phi'(\alpha)} = -\frac{f_x(x, y, \alpha)}{f_y(x, y, \alpha)}, \text{ or}$$

$$f_x(x, y, \alpha)\phi'(\alpha) + f_y(x, y, \alpha)\psi'(\alpha) = 0.$$

Comparing (6) and (3) gives

$$(7) \quad f_\alpha(x, y, \alpha) = 0.$$

Therefore the coördinates of the point of tangency satisfy

$$(8) \quad f(x, y, \alpha) = 0 \quad \text{and} \quad f_\alpha(x, y, \alpha) = 0;$$

that is, the parametric equations of the envelope, in case an envelope exists, may be found by solving these equations for x and y in terms of the parameter α .

General rule for finding the parametric equations of the envelope

FIRST STEP. Write the equation of the family of curves in the form $f(x, y, \alpha) = 0$ and derive the equation $f_\alpha(x, y, \alpha) = 0$.

SECOND STEP. Solve these two equations for x and y in terms of the parameter α .

The rectangular equation may be found either by eliminating α between the equations (8) or from the parametric equations (Art. 81).

ILLUSTRATIVE EXAMPLE 1. For the family of circles at the beginning of this article,

$$f(x, y, \alpha) = (x - \alpha)^2 + y^2 - r^2 = 0.$$

Hence
$$f_\alpha(x, y, \alpha) = (x - \alpha) = 0.$$

Eliminating α , the result is $y^2 - r^2 = 0$, or $y = r$, $y = -r$, and these are the equations of the lines AB and CD in the figure.

ILLUSTRATIVE EXAMPLE 2. Find the envelope of the family of straight lines $x \cos \alpha + y \sin \alpha = p$, α being the variable parameter.

Solution. (9)
$$f(x, y, \alpha) = x \cos \alpha + y \sin \alpha - p = 0.$$

First Step. Differentiating with respect to α ,

$$(10) \quad f_{\alpha}(x, y, \alpha) = -x \sin \alpha + y \cos \alpha = 0.$$

Second Step. Multiplying (9) by $\cos \alpha$ and (10) by $\sin \alpha$ and subtracting, we get

$$x = p \cos \alpha.$$

Similarly, eliminating x between (9) and (10),

$$y = p \sin \alpha.$$

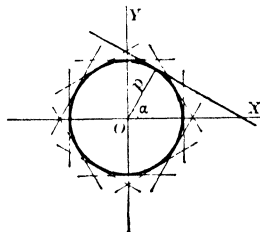
The parametric equations of the envelope are therefore

$$(11) \quad \begin{cases} x = p \cos \alpha, \\ y = p \sin \alpha, \end{cases}$$

α being the parameter. Squaring equations (11) and adding, we get

$$x^2 + y^2 = p^2,$$

the rectangular equation of the envelope, a circle.



ILLUSTRATIVE EXAMPLE 3. Find the envelope of a line of constant length a , whose extremities move along two fixed rectangular axes.

Solution. Let $AB = a$ in length, and let

$$(12) \quad x \cos \alpha + y \sin \alpha - p = 0$$

be its equation. Now as AB moves, both α and p will vary. But p may be found in terms of α . For $AO = AB \cos \alpha = a \cos \alpha$, and also $p = AO \sin \alpha = a \sin \alpha \cos \alpha$. Substituting in (12), we get

$$(13) \quad x \cos \alpha + y \sin \alpha - a \sin \alpha \cos \alpha = 0,$$

where α is the variable parameter. This equation is in the form $f(x, y, \alpha) = 0$. Differentiating with respect to α , the equation $f_{\alpha}(x, y, \alpha) = 0$ is

$$(14) \quad -x \sin \alpha + y \cos \alpha + a \sin^2 \alpha - a \cos^2 \alpha = 0.$$

Solving (13) and (14) for x and y in terms of α , the result is

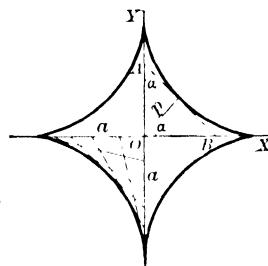
$$(15) \quad \begin{cases} x = a \sin^3 \alpha, \\ y = a \cos^3 \alpha, \end{cases}$$

the parametric equations of the envelope, a hypocycloid. The corresponding rectangular equation is found from equations (15) by eliminating α as follows:

$$x^{\frac{2}{3}} = a^{\frac{2}{3}} \sin^2 \alpha,$$

$$y^{\frac{2}{3}} = a^{\frac{2}{3}} \cos^2 \alpha.$$

Adding, $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$, the rectangular equation of the hypocycloid.



Many problems occur in which it is convenient to use two parameters connected by an equation of condition. By using the latter, one parameter may be eliminated from the equation of the family of curves. It is, however, often better to proceed as in the following example.

ILLUSTRATIVE EXAMPLE 4. Find the envelope of the family of ellipses whose axes coincide and whose area is constant.

Solution. (16) $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$

is the equation of the ellipse, where a and b are the variable parameters connected by the equation

$$(17) \quad \pi ab = k,$$

πab being the area of an ellipse whose semiaxes are a and b . Differentiating, regarding a and b as variables and x and y as constants, we have, using differentials,

$$\frac{x^2 da}{a^3} + \frac{y^2 db}{b^3} = 0, \text{ from (16),}$$

and $b da + a db = 0$, from (17).

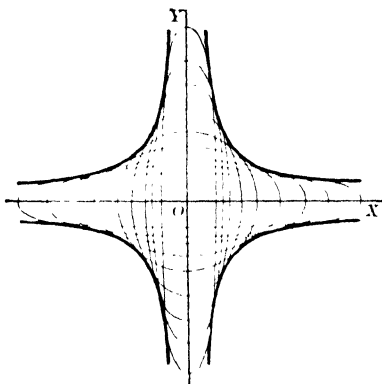
Transposing one term in each to the second member and dividing, the result is

$$\frac{x^2}{a^2} = \frac{y^2}{b^2}.$$

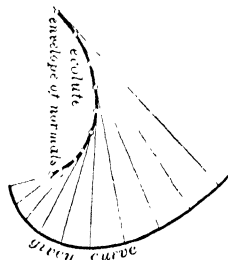
Therefore, using (16), $\frac{x^2}{a^2} = \frac{1}{2}$ and $\frac{y^2}{b^2} = \frac{1}{2}$.

whence $a = \pm x\sqrt{2}$ and $b = \pm y\sqrt{2}$.

Substituting these values in (17), we get the envelope $xy = \pm \frac{k}{2\pi}$, a pair of conjugate rectangular hyperbolas (see figure).



234. The evolute of a given curve considered as the envelope of its normals. Since the normals to a curve are all tangent to the evolute (Art. 110), it is evident that *the evolute of a curve may be defined as the envelope of its normals*. It is also interesting to notice that if we find the parametric equations of the envelope by the method of the previous article, we get the coördinates x and y of the center of curvature; so that we have here a *second method for finding the coördinates of the center of curvature*. If we eliminate the variable parameter, we obtain the rectangular equation of the evolute.



ILLUSTRATIVE EXAMPLE. Find the evolute of the parabola $y^2 = 4px$ considered as the envelope of its normals.

Solution. The equation of the normal at any point (x_1, y_1) is

$$y - y_1 = -\frac{y_1}{2p}(x - x_1)$$

from (2), Art. 43. As we are considering the normals all along the curve, both x_1 and y_1 will vary. Eliminating x_1 by means of $y_1^2 = 4px_1$, we find the equation of the normal to be

$$(1) \quad y - y_1 = \frac{y_1^3}{8p^2} - \frac{xy_1}{2p}, \quad \text{or} \quad xy_1 + 2py - 2py_1 - \frac{y_1^3}{4p} = 0.$$

Setting the partial derivative of the left-hand member with respect to the parameter y_1 equal to zero, and solving for x , we find

$$(2) \quad x = \frac{3y_1^2 + 8p^2}{4p}.$$

Substituting this value of x in (1) and solving for y ,

$$(3) \quad y = -\frac{y_1^4}{4p^2}.$$

Equations (2) and (3) are the coordinates of the center of curvature of the parabola. Taken together, they are the parametric equations of the evolute in terms of the parameter y_1 . Eliminating y_1 , we obtain

$$27py^2 = 4(x - 2p)^3,$$

the rectangular equation of the evolute of the parabola. This is the same result we obtained in Illustrative Example 1, Art. 109, by the first method.

PROBLEMS

Find the envelopes of the following systems of straight lines and draw the figures.

1. $y = mx + m^2.$

Ans. $x^2 + 4y = 0.$

2. $y = \frac{x}{m} + m^2.$

$27x^2 = 4y^3.$

3. $y = m^2x - 2m^3.$

$27y = x^3.$

4. $y = 2mx + m^4.$

$16y^3 + 27x^4 = 0.$

5. $y = tx - t^2.$

6. $y = t^2x + t.$

7. $y = mx - 2m^2.$

Find the envelopes of the following systems of circles and draw the figures.

8. $(x - c)^2 + y^2 = 4c.$

Ans. $y^2 = 4x + 4.$

9. $x^2 + (y - t)^2 = 2t.$

10. $(x - t)^2 + (y + t)^2 = t^2.$

Find the envelopes of the following systems of parabolas.

11. $y^2 = c(x - c).$

Ans. $2y = \pm x.$

12. $cy^2 = 1 - c^2x.$

13. Find the evolute of the ellipse $b^2x^2 + a^2y^2 = a^2b^2$, taking the equation of the normal in the form $by = ax \tan \phi - (a^2 - b^2) \sin \phi$, the eccentric angle ϕ being the parameter.

Ans. $x = \frac{a^2 - b^2}{a} \cos^3 \phi, y = \frac{b^2 - a^2}{b} \sin^3 \phi; \text{ or } (ax)^{\frac{2}{3}} + (by)^{\frac{2}{3}} = (a^2 - b^2)^{\frac{2}{3}}.$

14. Find the evolute of the hypocycloid $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$, the equation of whose normal is

$$y \cos \tau - x \sin \tau = a \cos 2 \tau,$$

τ being the parameter.

Ans. $(x+y)^{\frac{2}{3}} + (x-y)^{\frac{2}{3}} = 2a^{\frac{2}{3}}.$

15. Find the envelope of the circles which pass through the origin and have their centers on the hyperbola $x^2 - y^2 = c^2$.

Ans. The lemniscate $(x^2 + y^2)^2 = 4c^2(x^2 - y^2).$

16. Find the envelope of a line such that the sum of its intercepts on the axes equals c .

Ans. The parabola $x^{\frac{1}{2}} + y^{\frac{1}{2}} = c^{\frac{1}{2}}.$

17. Find the envelope of the family of ellipses $b^2x^2 + a^2y^2 = a^2b^2$ when the sum of its semiaxes equals c .

Ans. The hypocycloid $x^{\frac{2}{3}} + y^{\frac{2}{3}} = c^{\frac{2}{3}}.$

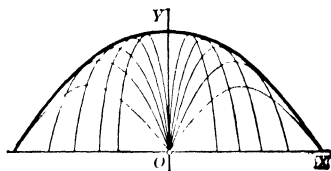
18. Projectiles are fired from a gun with an initial velocity v_0 . Supposing the gun can be given any elevation and is kept always in the same vertical plane, what is the envelope of all possible trajectories, the resistance of the air being neglected?

HINT. The equation of any trajectory is

$$y = x \tan \alpha - \frac{gx^2}{2v_0^2 \cos^2 \alpha},$$

α being the variable parameter.

Ans. The parabola $y = \frac{v_0^2}{2g} - \frac{gx^2}{2v_0^2}.$



19. If the family

$$t^2f(x, y) + tg(x, y) + h(x, y) = 0$$

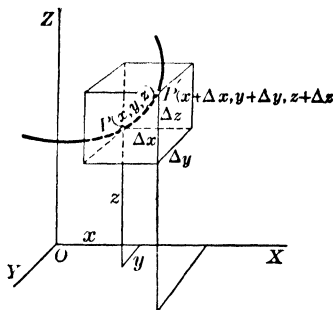
has an envelope, show that it is

$$g^2(x, y) - 4f(x, y)h(x, y) = 0.$$

235. **Tangent line and normal plane to a skew curve.** The student is already familiar with the parametric representation of a plane curve (Art. 81). In order to extend this notion to curves in space, let the coördinates of any point $P(x, y, z)$ on a skew curve be given as functions of some fourth variable which we shall denote by t ; thus,

$$(1) \quad x = \phi(t), \quad y = \psi(t), \quad z = \chi(t).$$

The elimination of the parameter t between these equations two by two will give us the equations of the projecting cylinders of the curve on the coördinate planes.



Let the point $P(x, y, z)$ correspond to the value t of the parameter, and the point $P'(x + \Delta x, y + \Delta y, z + \Delta z)$ correspond to the value $t + \Delta t$ where $\Delta x, \Delta y, \Delta z$ are the increments of x, y, z due to the increment Δt as found from equations (1). From analytic geometry of three dimensions, we know that the direction cosines of the secant (diagonal) PP' are proportional to

$$\Delta x, \Delta y, \Delta z;$$

or, dividing through by Δt and denoting the direction angles of the secant by α', β', γ' ,

$$(2) \quad \frac{\cos \alpha'}{\frac{\Delta x}{\Delta t}} = \frac{\cos \beta'}{\frac{\Delta y}{\Delta t}} = \frac{\cos \gamma'}{\frac{\Delta z}{\Delta t}}.$$

Now let P' approach P along the curve. Then Δt , and therefore also $\Delta x, \Delta y, \Delta z$, will approach zero as a limit, and the secant PP' will approach the tangent line to the curve at P as a limiting position.

$$\text{Now} \quad \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt} = \phi'(t), \text{ etc.}$$

Hence, for the tangent line,

$$(A) \quad \frac{\cos \alpha}{\frac{dx}{dt}} = \frac{\cos \beta}{\frac{dy}{dt}} = \frac{\cos \gamma}{\frac{dz}{dt}}.$$

When the point of contact is $P_1(x_1, y_1, z_1)$, we use the notation

$$(3) \quad \left| \frac{dx}{dt} \right|_1 = \text{value of } \frac{dx}{dt} \text{ when } x = x_1, y = y_1, z = z_1,$$

and similar notation for the other derivatives.

Hence, by (2) and (4), p. 5, we have the following result.

The equations of the tangent line to the curve whose equations are

$$(1) \quad x = \phi(t), \quad y = \psi(t), \quad z = \chi(t)$$

at the point $P_1(x_1, y_1, z_1)$ are

$$(B) \quad \frac{x - x_1}{\left| \frac{dx}{dt} \right|_1} = \frac{y - y_1}{\left| \frac{dy}{dt} \right|_1} = \frac{z - z_1}{\left| \frac{dz}{dt} \right|_1}.$$

The *normal plane* of a skew curve at a point $P_1(x_1, y_1, z_1)$ is the plane which passes through P_1 and is perpendicular to the tangent line at P_1 . The denominators in (B) are the direction numbers of the tangent line at P_1 . Hence we have the following result.

The equation of the normal plane to the curve (1) at $P_1(x_1, y_1, z_1)$ is

$$(C) \quad \left| \frac{dx}{dt} \right|_1 (x - x_1) + \left| \frac{dy}{dt} \right|_1 (y - y_1) + \left| \frac{dz}{dt} \right|_1 (z - z_1) = 0.$$

ILLUSTRATIVE EXAMPLE. Find the equations of the tangent line and the equation of the normal plane to the circular helix (θ being the parameter)

$$(4) \quad \begin{cases} x = a \cos \theta, \\ y = a \sin \theta, \\ z = b\theta, \end{cases}$$

(a) at any point (x_1, y_1, z_1) ; (b) when $\theta = 2\pi$.

Solution. $\frac{dx}{d\theta} = -a \sin \theta = -y, \quad \frac{dy}{d\theta} = a \cos \theta = x, \quad \frac{dz}{d\theta} = b.$

Substituting in (B) and (C), we get, at (x_1, y_1, z_1) ,

$$(5) \quad \frac{x - x_1}{-y_1} = \frac{y - y_1}{x_1} = \frac{z - z_1}{b}, \text{ tangent line,}$$

and

$$-y_1(x - x_1) + x_1(y - y_1) + b(z - z_1) = 0,$$

normal plane.

When $\theta = 2\pi$, the point on the curve is $T(a, 0, 2b\pi)$, giving

$$\frac{x - a}{0} = \frac{y - 0}{a} = \frac{z - 2b\pi}{b},$$

or $x = a, \quad by = az - 2ab\pi,$

the equations of the tangent line, and

$$ay + bz - 2b^2\pi = 0,$$

the equation of the normal plane.

REMARK. For the tangent line (5) we have by (2) and (4), p. 5,

$$\cos \gamma = \frac{b}{\sqrt{x_1^2 + y_1^2 + b^2}} = \frac{b}{\sqrt{a^2 + b^2}} = \text{a constant}$$

That is, the helix cuts all elements of the cylinder $x^2 + y^2 = a^2$ under the same angle.

236. Length of arc of a skew curve. From the figure of the preceding article we have

$$(1) \quad \frac{(\text{Chord } PP')^2}{\Delta t^2} = \left(\frac{\Delta x}{\Delta t} \right)^2 + \left(\frac{\Delta y}{\Delta t} \right)^2 + \left(\frac{\Delta z}{\Delta t} \right)^2.$$

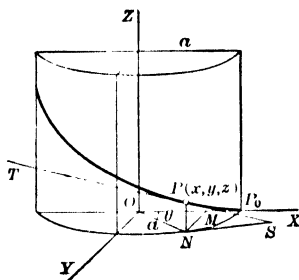
Let arc $PP' = \Delta s$. Proceeding as in Art. 95, we easily prove

$$(2) \quad \left(\frac{ds}{dt} \right)^2 = \left(\frac{dx}{dt} \right)^2 + \left(\frac{dy}{dt} \right)^2 + \left(\frac{dz}{dt} \right)^2.$$

From this we obtain

$$(D) \quad s = \int_{t_0}^{t_1} (dx^2 + dy^2 + dz^2)^{\frac{1}{2}},$$

where $x = \phi(t)$, $y = \psi(t)$, $z = \chi(t)$, as in (1), Art. 235.



The direction cosines of the tangent line can now be given a simple form. For, from (A) of the preceding article, and by the above equation (2), using formulas in (2), p. 5, we have

$$(3) \quad \cos \alpha = \frac{dx}{ds}, \quad \cos \beta = \frac{dy}{ds}, \quad \cos \gamma = \frac{dz}{ds}.$$

ILLUSTRATIVE EXAMPLE. Find the length of arc of the skew cubic

$$(4) \quad x = t, \quad y = \frac{1}{2} t^2, \quad z = \frac{1}{3} t^3$$

between the points where $t = 0$ and $t = 4$.

Solution. Differentiating (4), we obtain

$$dx = dt, \quad dy = t \, dt, \quad dz = t^2 \, dt.$$

$$\text{Substituting in (D),} \quad s = \int_0^4 \sqrt{1 + t^2 + t^4} \, dt = 23.92,$$

approximately, by Simpson's Rule, letting $n = 8$.

PROBLEMS

Find the equations of the tangent line and the equation of the normal plane to each of the following skew curves at the point indicated.

1. $x = at, y = bt^2, z = ct^3; t = 1$.

$$\text{Ans.} \quad \frac{x-a}{a} = \frac{y-b}{2b} = \frac{z-c}{3c}; \quad ax + 2by + 3cz = a^2 + 2b^2 + 3c^2.$$

2. $x = 2t, y = t^2, z = 4t^4; t = 1$.

$$\text{Ans.} \quad \frac{x-2}{2} = \frac{y-1}{2} = \frac{z-4}{16}; \quad x + y + 8z = 35.$$

3. $x = t^2 - 1, y = t + 1, z = t^3; t = 2$.

$$\text{Ans.} \quad \frac{x-3}{4} = \frac{y-3}{1} = \frac{z-8}{12}; \quad 4x + y + 12z = 111.$$

4. $x = t^3 - 1, y = t^2 + t, z = 4t^3 - 3t + 1; t = 1$.

$$\text{Ans.} \quad \frac{x}{3} = \frac{y-2}{3} = \frac{z-2}{9}; \quad x + y + 3z = 8.$$

5. $x = 2t - 3, y = 5 - t^2, z = \frac{2}{t}; t = 2$.

6. $x = a \cos t, y = b \sin t, z = t; t = \frac{1}{6} \pi$.

7. $x = t, y = e^t, z = e^{-t}; t = 0$.

8. $x = \cos t, y = \sin t, z = \tan t; t = 0$.

9. Find the length of arc of the circular helix

$$x = a \cos \theta, \quad y = a \sin \theta, \quad z = b\theta$$

between the points where $\theta = 0$ and $\theta = 2\pi$.

$$\text{Ans.} \quad 2\pi\sqrt{a^2 + b^2}.$$

10. Find the length of arc of the curve

$$x = 3 \theta \cos \theta, \quad y = 3 \theta \sin \theta, \quad z = 4 \theta$$

between the points where $\theta = 0$ and $\theta = 4$. Ans. $26 + \frac{2}{3} \ln 5 = 32.70$.

11. Find the length of arc of the curve

$$x = 2t, \quad y = t^2 - 2, \quad z = 1 - t^2$$

between the points where $t = 0$ and $t = 2$.

12. Given the two curves

(5) $x = t, \quad y = 2t^2, \quad z = -\frac{1}{t};$

(6) $x = 1 - \theta, \quad y = 2 \cos \theta, \quad z = \sin \theta - 1.$

(a) Show that the two curves intersect at the point $A(1, 2, -1)$.

(b) Find the direction cosines of the tangent line to (5) at A .

$$\text{Ans. } \frac{1}{\sqrt{18}}, \frac{4}{\sqrt{18}}, \frac{1}{\sqrt{18}}.$$

(c) Find the direction cosines of the tangent line to (6) at A .

(d) Find the angle of intersection of the curves at A . Ans. 90° .

13. Given the two curves

$$x = 2 - t, \quad y = t^2 - 4, \quad z = t^3 - 8;$$

$$x = \sin \theta, \quad y = \theta, \quad z = 1 - \cos \theta.$$

(a) Show that the two curves intersect at the origin O .

(b) Find the direction cosines of the tangent line to each curve at O .

(c) Find the angle of intersection of the curves at O .

14. (a) If OF , OE , ON in the first figure of Art. 222 are chosen as axes of coördinates OX , OY , OZ , respectively, and if $P(x, y, z)$ is a point on the sphere, prove that $x = a \cos \phi \sin \theta$, $y = a \cos \phi \cos \theta$, $z = a \sin \phi$, if ϕ and θ are, respectively, the latitude and longitude of P .

(b) Using (3), and (3) on page 5, find the angle α at P between a curve on the sphere for which $\theta = f(\phi)$ and the parallel through P .

$$\text{Ans. } \tan \alpha = \sec \phi \frac{d\phi}{d\theta}, \text{ as in Art. 222.}$$

237. Normal line and tangent plane to a surface. A straight line is said to be *tangent to a surface* at a point P if it is the limiting position of a secant line through P and a neighboring point P' on the surface when P' is made to approach P along a curve on the surface. We now proceed to establish a theorem of fundamental importance.

Theorem. *All tangent lines to a surface at a given point lie in a plane.*

Proof. Let

(1) $F(x, y, z) = 0$

be the equation of the given surface, and let $P(x, y, z)$ be the given point on the surface. If now P' be made to approach P along a curve

C lying on the surface and passing through P and P' , then evidently the secant line PP' approaches the position of a tangent line to the curve C at P . Now let the equations of the curve C be

$$(2) \quad x = \phi(t), \quad y = \psi(t), \quad z = \chi(t).$$

Then the equation (1) must be satisfied identically by these values. Hence, if $u = F(x, y, z)$, then $u = 0$, $du = 0$, and by (E), Art. 229,

$$(3) \quad \frac{\partial F}{\partial x} \frac{dx}{dt} + \frac{\partial F}{\partial y} \frac{dy}{dt} + \frac{\partial F}{\partial z} \frac{dz}{dt} = 0.$$

This equation (see (3), Art. 4) shows that the tangent line to (2), whose direction cosines are proportional to

$$\frac{dx}{dt}, \quad \frac{dy}{dt}, \quad \frac{dz}{dt},$$

is perpendicular to a line whose direction cosines are proportional to

$$(4) \quad \frac{\partial F}{\partial x}, \quad \frac{\partial F}{\partial y}, \quad \frac{\partial F}{\partial z}. \quad \text{By (3), p. 5}$$

Let $P_1(x_1, y_1, z_1)$ be a point on the surface and

$$(5) \quad \left| \frac{\partial F}{\partial x} \right|_1, \quad \left| \frac{\partial F}{\partial y} \right|_1, \quad \left| \frac{\partial F}{\partial z} \right|_1$$

the values of the partial derivatives in (4) when $x = x_1$, $y = y_1$, $z = z_1$. The line passing through P_1 whose direction numbers are given by (5) is called the *normal line* to the surface at P_1 . Hence we have the following result:

The equations of the normal line to the surface

$$(1) \quad F(x, y, z) = 0$$

at $P_1(x_1, y_1, z_1)$ are

$$(E) \quad \frac{x - x_1}{\left| \frac{\partial F}{\partial x} \right|_1} = \frac{y - y_1}{\left| \frac{\partial F}{\partial y} \right|_1} = \frac{z - z_1}{\left| \frac{\partial F}{\partial z} \right|_1}.$$

The preceding argument shows that *all* tangent lines to the surface (1) at P_1 are perpendicular to the normal line at P_1 . Hence they lie in a plane. Thus the theorem is proved.

This plane is called the *tangent plane* at (P_1) .

We may now state the following result.

The equation of the tangent plane to the surface (1) at the point of contact $P_1(x_1, y_1, z_1)$ is

$$(F) \quad \left| \frac{\partial F}{\partial x} \right|_1 (x - x_1) + \left| \frac{\partial F}{\partial y} \right|_1 (y - y_1) + \left| \frac{\partial F}{\partial z} \right|_1 (z - z_1) = 0.$$

REMARK. If all the denominators in (E) vanish, the normal line and tangent plane are indeterminate. Such points are called *singular points* and are excluded here.

In case the equation of the surface is given in the form $z = f(x, y)$, let

$$(6) \quad F(x, y, z) = f(x, y) - z = 0.$$

$$\text{Then} \quad \frac{\partial F}{\partial x} = \frac{\partial f}{\partial x} = \frac{\partial z}{\partial x}, \quad \frac{\partial F}{\partial y} = \frac{\partial f}{\partial y} = \frac{\partial z}{\partial y}, \quad \frac{\partial F}{\partial z} = -1.$$

Hence, by (E), we have the following result.

The equations of the normal line to the surface $z = f(x, y)$ at (x_1, y_1, z_1) are

$$(G) \quad \frac{x - x_1}{\left| \frac{\partial z}{\partial x} \right|_1} = \frac{y - y_1}{\left| \frac{\partial z}{\partial y} \right|_1} = \frac{z - z_1}{-1}.$$

Also, from (F), we obtain

$$(H) \quad \left| \frac{\partial z}{\partial x} \right|_1 (x - x_1) + \left| \frac{\partial z}{\partial y} \right|_1 (y - y_1) - (z - z_1) = 0,$$

which is then the formula for the equation of a plane tangent at (x_1, y_1, z_1) to a surface whose equation is given in the form $z = f(x, y)$.

238. Geometric interpretation of the total differential. We are now in a position to discuss formula (B), Art. 227, by geometry, in a manner entirely analogous to that in Art. 91.

Consider the surface

$$(1) \quad z = f(x, y),$$

and the point (x_1, y_1, z_1) on it. Then the total differential of (1) is, when

$$(2) \quad dz = \left| \frac{\partial z}{\partial x} \right|_1 \Delta x + \left| \frac{\partial z}{\partial y} \right|_1 \Delta y,$$

using (B), Art. 227, and replacing dx and dy by their equivalents, Δx and Δy , respectively. Let us find the z -coördinate of the point in the tangent plane at P_1 where

$$x = x_1 + \Delta x, \quad y = y_1 + \Delta y.$$

Substituting these values in (H) of Art. 237, we find

$$(3) \quad z - z_1 = \left| \frac{\partial z}{\partial x} \right|_1 \Delta x + \left| \frac{\partial z}{\partial y} \right|_1 \Delta y.$$

Comparing (2) and (3), we get $dz = z - z_1$. Hence the

Theorem. *The total differential of a function $f(x, y)$ corresponding to the increments Δx and Δy equals the corresponding increment of the z -coordinate of the tangent plane to the surface $z = f(x, y)$.*

Thus, in the figure, PP' is the plane tangent to surface PQ at $P(x, y, z)$.

Let $AB = \Delta x$

and $CD = \Delta y$;

then $dz = z - z_1 = DP' - DE = EP'$.

Notice also that $\Delta z = DQ - DE = EQ$.

ILLUSTRATIVE EXAMPLE. Find the equation of the tangent plane and the equations of the normal line to the sphere $x^2 + y^2 + z^2 = 14$ at the point $(1, 2, 3)$.

Solution. Let $F(x, y, z) = x^2 + y^2 + z^2 - 14$;

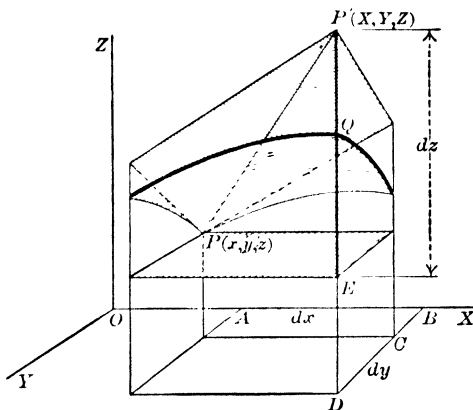
then $\frac{\partial F}{\partial x} = 2x$, $\frac{\partial F}{\partial y} = 2y$, $\frac{\partial F}{\partial z} = 2z$; $x_1 = 1$, $y_1 = 2$, $z_1 = 3$.

Therefore $\left| \frac{\partial F}{\partial x} \right|_1 = 2$, $\left| \frac{\partial F}{\partial y} \right|_1 = 4$, $\left| \frac{\partial F}{\partial z} \right|_1 = 6$.

Substituting in (F), $2(x-1) + 4(y-2) + 6(z-3) = 0$,
or $x + 2y + 3z = 14$, the tangent plane.

Substituting in (E), $\frac{x-1}{2} = \frac{y-2}{4} = \frac{z-3}{6}$,

giving $z = 3x$ and $2z = 3y$, equations of the normal line. *Ans.*



PROBLEMS

Find the equation of the tangent plane and the equations of the normal line to each of the following surfaces at the point indicated.

1. $x^2 + y^2 + z^2 = 49$; $(6, 2, 3)$.

Ans. $6x + 2y + 3z = 49$; $\frac{x-6}{6} = \frac{y-2}{2} = \frac{z-3}{3}$.

2. $z = x^2 + y^2 - 1$; $(2, 1, 4)$.

Ans. $4x + 2y - z = 6$; $\frac{x-2}{4} = \frac{y-1}{2} = \frac{z-4}{-1}$.

3. $x^2 + xy^2 + y^3 + z + 1 = 0$; $(2, -3, 4)$.

Ans. $13x + 15y + z + 15 = 0$; $\frac{x-2}{13} = \frac{y+3}{15} = \frac{z-4}{1}$.

4. $x^2 + 2xy + y^2 + z - 7 = 0$; $(1, -2, 6)$.

Ans. $2x + 2y - z + 8 = 0$; $\frac{x-1}{2} = \frac{y+2}{2} = \frac{z-6}{-1}$.

5. $x^2y^2 + xz - 2y^3 - 10 = 0$; $(2, 1, 4)$.

Ans. $4x + y + z - 13 = 0$; $\frac{x-2}{4} = \frac{y-1}{1} = \frac{z-4}{1}$.

6. $x^2 - y^2 - z^2 = 1$; $(3, 2, 2)$.

7. $x^2 + y^2 - z^2 = 25$; $(5, 5, 5)$.

8. $2x^2 + 3y^2 + 4z^2 = 6$; $(1, 1, \frac{1}{2})$.

9. $x + y - z^2 = 3$; $(3, 4, 2)$.

10. Find the equation of the tangent plane to the hyperboloid of two sheets $\frac{x^2}{a^2} - \frac{y^2}{b^2} - \frac{z^2}{c^2} = 1$ at (x_1, y_1, z_1) . *Ans.* $\frac{x_1x}{a^2} - \frac{y_1y}{b^2} - \frac{z_1z}{c^2} = 1$.

11. Find the equation of the tangent plane at the point (x_1, y_1, z_1) on the surface $ax^2 + by^2 + cz^2 + d = 0$. *Ans.* $ax_1x + by_1y + cz_1z + d = 0$.

12. Show that the equation of the plane tangent to the sphere

$$x^2 + y^2 + z^2 + 2Lx + 2My + 2Nz + D = 0$$

at the point (x_1, y_1, z_1) is

$$x_1x + y_1y + z_1z + L(x + x_1) + M(y + y_1) + N(z + z_1) + D = 0.$$

13. Find the equation of the tangent plane at any point of the surface

$$x^{\frac{2}{3}} + y^{\frac{2}{3}} + z^{\frac{2}{3}} = a^{\frac{2}{3}},$$

and show that the sum of the squares of the intercepts on the axes made by the tangent plane is constant.

14. Prove that the tetrahedron formed by the coordinate planes and any tangent plane to the surface $xyz = a^3$ is of constant volume.

15. The surface $x^2 - 4y^2 - 4z = 0$ is cut by the curve $x = \frac{t^2}{2}$, $y = \frac{4}{t}$, $z = \frac{t-2}{2} \frac{t^2}{2}$ at the point $(2, 2, -3)$. What is the angle of intersection?

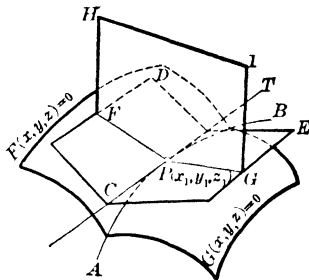
Ans. $90^\circ - \arccos \frac{19}{3\sqrt{138}} = 32^\circ 37'$.

16. The surface $x^2 + y^2 + 3z^2 = 25$ and the curve $x = 2t$, $y = \frac{3}{t}$, $z = -2t^2$ intersect at the point on the curve given by $t = 1$. What is the angle of intersection?

Ans. $90^\circ - \arccos \frac{19}{7\sqrt{29}} = 30^\circ 16'$.

17. The ellipsoid $x^2 + 2y^2 + 3z^2 = 20$ and the skew curve $x = \frac{3}{2}(t^2 + 1)$, $y = t^4 + 1$, $z = t^3$ meet at the point $(3, 2, 1)$. Show that the curve cuts the surface orthogonally.

239. Another form of the equations of the tangent line and normal plane to a skew curve. If the curve in question be the curve of intersection AB of the two surfaces $F(x, y, z) = 0$ and $G(x, y, z) = 0$, the tangent line PT at $P(x_1, y_1, z_1)$ is the intersection of the tangent planes CD and CE at that point, for it is also tangent to both surfaces and hence must lie in both tangent planes. The equations of the two tangent planes at P are, from (F),



$$(1) \quad \left| \frac{\partial F}{\partial x} \right|_1 (x - x_1) + \left| \frac{\partial F}{\partial y} \right|_1 (y - y_1) + \left| \frac{\partial F}{\partial z} \right|_1 (z - z_1) = 0,$$

$$\left| \frac{\partial G}{\partial x} \right|_1 (x - x_1) + \left| \frac{\partial G}{\partial y} \right|_1 (y - y_1) + \left| \frac{\partial G}{\partial z} \right|_1 (z - z_1) = 0.$$

Taken simultaneously, these equations are the equations of the tangent line PT to the skew curve AB .

If A, B, C are direction numbers for the line of intersection of the planes (1), then, by (6), Art. 4,

$$(2) \quad A = \left| \frac{\partial F}{\partial y} \right|_1 \left| \frac{\partial G}{\partial z} \right|_1 - \left| \frac{\partial F}{\partial z} \right|_1 \left| \frac{\partial G}{\partial y} \right|_1, \quad B = \left| \frac{\partial F}{\partial z} \right|_1 \left| \frac{\partial G}{\partial x} \right|_1 - \left| \frac{\partial F}{\partial x} \right|_1 \left| \frac{\partial G}{\partial z} \right|_1,$$

$$C = \left| \frac{\partial F}{\partial x} \right|_1 \left| \frac{\partial G}{\partial y} \right|_1 - \left| \frac{\partial F}{\partial y} \right|_1 \left| \frac{\partial G}{\partial x} \right|_1.$$

Then the equations of the tangent line CPT are

$$(3) \quad \frac{x - x_1}{A} = \frac{y - y_1}{B} = \frac{z - z_1}{C}.$$

The equation of the normal plane PHI is

$$(4) \quad A(x - x_1) + B(y - y_1) + C(z - z_1) = 0.$$

ILLUSTRATIVE EXAMPLE 1. Find the equations of the tangent line and the equation of the normal plane at $(r, r, r\sqrt{2})$ to the curve of intersection of the sphere and cylinder whose equations are, respectively, $x^2 + y^2 + z^2 = 4r^2$, $x^2 + y^2 = 2rx$.

Solution. Let $F = x^2 + y^2 + z^2 - 4r^2$ and $G = x^2 + y^2 - 2rx$.

$$\left| \frac{\partial F}{\partial x} \right|_1 = 2r, \quad \left| \frac{\partial F}{\partial y} \right|_1 = 2r, \quad \left| \frac{\partial F}{\partial z} \right|_1 = 2r\sqrt{2};$$

$$\left| \frac{\partial G}{\partial x} \right|_1 = 0, \quad \left| \frac{\partial G}{\partial y} \right|_1 = 2r, \quad \left| \frac{\partial G}{\partial z} \right|_1 = 0.$$

Substituting in (2), we find

$$A = -4r^2\sqrt{2}, \quad B = 0, \quad C = 4r^2.$$

Hence, by (3), we have

$$\frac{x-r}{-\sqrt{2}} = \frac{y-r}{0} = \frac{z-r\sqrt{2}}{1};$$

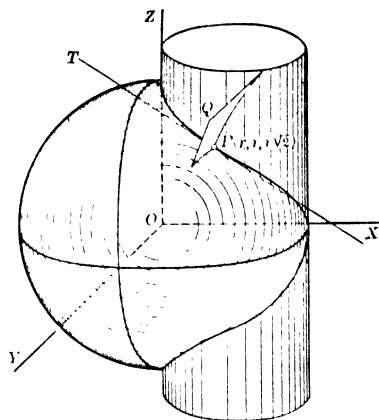
or $y = r, \quad x + \sqrt{2}z = 3r,$

the equations of the tangent PT at P to the curve of intersection.

Substituting in (4), we get the equation of the normal plane,

$$-\sqrt{2}(x-r) + 0(y-r) + (z-r\sqrt{2}) = 0,$$

or $\sqrt{2}x - z = 0.$



ILLUSTRATIVE EXAMPLE 2. Find the angle of intersection of the surfaces in the preceding example at the point given.

Solution. The angle of intersection equals the angle between the tangent planes or normal lines. We have found direction numbers for these lines above in Illustrative Example 1 (see (E), Art. 237).

These are $a = 2r, \quad b = 2r, \quad c = 2r\sqrt{2}.$

$$a' = 0, \quad b' = 2r, \quad c' = 0.$$

Hence, by (6), Art. 4

$$\cos \theta = \frac{4r^2}{8r^2} = \frac{1}{2}. \quad \theta = 60^\circ. \quad \text{Ans.}$$

PROBLEMS

Find the equations of the tangent line and the equation of the normal plane to each of the following curves at the point indicated.

1. $x^2 + y^2 + z^2 = 49, \quad x^2 + y^2 = 13; \quad (3, 2, -6).$

Ans. $\frac{x-3}{2} = \frac{y-2}{-3}, \quad z+6=0; \quad 2x-3y=0.$

2. $z = x^2 + y^2 - 1, \quad 3x^2 + 2y^2 + z^2 = 30; \quad (2, 1, 4).$

Ans. $\frac{x-2}{5} = \frac{y-1}{-11} = \frac{z-4}{-2}; \quad 5x-11y-2z+9=0.$

3. $x^2 + y^2 - z^2 = 16, \quad x^2 + 4y^2 + 4z^2 = 84; \quad (2, 4, 2).$

Ans. $\frac{x-2}{16} = \frac{y-4}{-5} = \frac{z-2}{6}; \quad 16x-5y+6z=24.$

4. $x^2 + y^2 + 3z^2 = 32, \quad 2x^2 + y^2 - z^2 = 0; \quad (2, 1, 3).$

Ans. $\frac{x-2}{6} = \frac{y-1}{-21} = \frac{z-3}{1}; \quad 6x-21y+z+6=0.$

5. $x^2 - y^2 - z^2 = 1, \quad x^2 - y^2 + z^2 = 9; \quad (3, 2, 2).$

6. $x^2 + 4y^2 - 4z^2 = 0, \quad 2x + y + z - 24 = 0; \quad (8, 3, 5).$

7. The equations of a helix (spiral) are

$$x^2 + y^2 = r^2, \\ y = x \tan \frac{z}{c}.$$

Show that at the point (x_1, y_1, z_1) the equations of the tangent line are

$$c(x - x_1) + y_1(z - z_1) = 0, \\ c(y - y_1) - x_1(z - z_1) = 0;$$

and the equation of the normal plane is

$$y_1x - x_1y - c(z - z_1) = 0.$$

8. The surfaces $x^2y^2 + 2x + z^3 = 16$ and $3x^2 + y^2 - 2z = 9$ intersect in a curve which passes through the point $(2, 1, 2)$. What are the equations of the respective tangent planes to the two surfaces at this point?

Ans. $3x + 4y + 6z = 22$; $6x + y - z = 11$.

9. Show that the ellipsoid $x^2 + 3y^2 + 2z^2 = 9$ and the sphere $x^2 + y^2 + z^2 - 8x - 6y - 6z + 24 = 0$ are tangent to each other at the point $(2, 1, 1)$.

10. Show that the paraboloid $3x^2 + 2y^2 - 2z = 1$ and the sphere $x^2 + y^2 + z^2 - 4y - 2z + 2 = 0$ cut orthogonally at the point $(1, 1, 2)$.

240. Law of the Mean. The applications of partial derivatives to be given now depend upon the Law of the Mean for functions of several variables. The result to be derived is based upon the discussion in Art. 116. We proceed to establish the formula

$$(1) \quad f(x_0 + h, y_0 + k) = f(x_0, y_0) + hf_x(x_0 + \theta h, y_0 + \theta k) \\ + kf_y(x_0 + \theta h, y_0 + \theta k). \quad (0 < \theta < 1)$$

To this end let

$$(2) \quad F(t) = f(x_0 + ht, y_0 + kt).$$

Apply (D), Art. 116, to $F(t)$, with $a = 0$, and $\Delta a = 1$. Then we have

$$(3) \quad F(1) = F(0) + F'(\theta). \quad (0 < \theta < 1)$$

But from (2), by (D), Art. 229, since $x = x_0 + ht$, $y = y_0 + kt$,

$$(4) \quad F'(t) = hf_x(x_0 + ht, y_0 + kt) + kf_y(x_0 + ht, y_0 + kt).$$

Then, from (2), we get

$$(5) \quad F(1) = f(x_0 + h, y_0 + k), \quad F(0) = f(x_0, y_0),$$

and, from (4),

$$(6) \quad F'(\theta) = hf_x(x_0 + \theta h, y_0 + \theta k) + kf_y(x_0 + \theta h, y_0 + \theta k).$$

When these results are substituted in (3), we obtain (1).

If we desire a formula analogous to (F), Art. 124, we must form $F''(t)$. Applying again (D), Art. 229, we get

$$\begin{aligned}\frac{d}{dt}f_x(x_0 + ht, y_0 + kt) &= hf_{xx}(x_0 + ht, y_0 + kt) + kf_{yx}(x_0 + ht, y_0 + kt); \\ \frac{d}{dt}f_y(x_0 + ht, y_0 + kt) &= hf_{xy}(x_0 + ht, y_0 + kt) + kf_{yy}(x_0 + ht, y_0 + kt).\end{aligned}$$

Hence from (4), we have by differentiating with respect to t ,

$$(7) \quad F''(t) = h^2 f_{xx}(x_0 + ht, y_0 + kt) + 2 h k f_{xy}(x_0 + ht, y_0 + kt) + k^2 f_{yy}(x_0 + ht, y_0 + kt).$$

From (F), Art. 124, letting $b = 1$, $a = 0$, $x_2 = \theta$, we get

$$(8) \quad F(1) = F(0) + F'(0) + \left[\frac{1}{2} F''(\theta) \right].$$

We may easily prove now the extended Law of the Mean for a function of two variables by substituting in (8) from (5), (4), and (7). Thus we get

$$\begin{aligned}(9) \quad f(x_0 + h, y_0 + k) &= f(x_0, y_0) + hf_x(x_0, y_0) + kf_y(x_0, y_0) \\ &+ \left[\frac{1}{2} [h^2 f_{xx}(x_0 + \theta h, y_0 + \theta k) + 2 h k f_{xy}(x_0 + \theta h, y_0 + \theta k) \right. \\ &\left. + k^2 f_{yy}(x_0 + \theta h, y_0 + \theta k) \right]. \quad (0 < \theta < 1).\end{aligned}$$

There is no difficulty in establishing the corresponding formulas for functions of more than two variables, nor in extending the laws in a manner analogous to that at the end of Art. 124.

241. Maxima and minima of functions of several variables. In Art. 46, and again in Art. 125, were derived necessary and sufficient conditions for maximum and minimum values of a function of one variable. We now take up this problem when several independent variables are present.

The function $f(x, y)$ is said to be a *maximum* at $x = a$, $y = b$ when $f(a, b)$ is greater than $f(x, y)$ for all values of x and y in the neighborhood of a and b . Similarly, $f(x, y)$ is said to be a *minimum* at $x = a$, $y = b$ when $f(a, b)$ is less than $f(x, y)$ for all values of x and y in the neighborhood of a and b .

These definitions may be stated in analytical form as follows:

If, for all values of h and k numerically less than some small positive quantity,

$$(1) \quad f(a + h, b + k) - f(a, b) = \text{a negative number,}$$

then $f(a, b)$ is a *maximum* value of $f(x, y)$. If

$$(2) \quad f(a + h, b + k) - f(a, b) = \text{a positive number,}$$

then $f(a, b)$ is a *minimum* value of $f(x, y)$.

These statements may be interpreted geometrically as follows. A point P on the surface

$$z = f(x, y)$$

is a maximum point when it is "higher" than all other points on the surface in its neighborhood, the coördinate plane XOY being assumed horizontal. Similarly, P' is a minimum point on the surface when it is "lower" than all other points on the surface in its neighborhood.

Hence if

$$z_1 = f(a, b)$$

is a maximum or minimum, the tangent plane

at (a, b, z_1) must be horizontal, that is, parallel to XOY . But the tangent plane (H), Art. 237, is parallel to XOY when the coefficients of x and y are zero. Hence we have the following result.

A necessary condition that $f(a, b)$ shall be a maximum or minimum value of $f(x, y)$ is that the equations

$$(3) \quad \frac{\partial f}{\partial x} = 0, \quad \frac{\partial f}{\partial y} = 0$$

shall be satisfied by $x = a, y = b$.

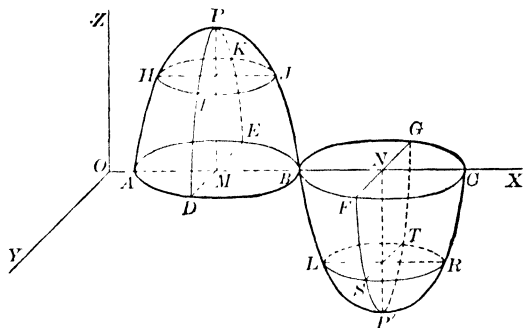
The conditions (3) may be obtained without use of the tangent plane. For, when $y = b$, the function $f(x, b)$ can neither increase nor decrease when x passes through a (see Art. 45). Hence follows the first of equations (3). The same statement applies to the function $f(a, y)$. Thus we have the second equation in (3).

The method just expounded applies to a function of three variables $f(x, y, z)$. That is, a necessary condition that $f(a, b, c)$ shall be a maximum or a minimum value is that the equations

$$(4) \quad \frac{\partial f}{\partial x} = 0, \quad \frac{\partial f}{\partial y} = 0, \quad \frac{\partial f}{\partial z} = 0$$

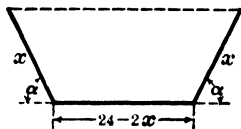
shall have the common solution $x = a, y = b, z = c$.

For necessary and sufficient conditions the problem is much more difficult (see below). But in many applied problems the existence of a maximum or minimum value is known in advance, and no test is necessary.



ILLUSTRATIVE EXAMPLE 1. A long piece of tin 24 in. wide is to be made into a trough by bending up two sides. Find the width and inclination of each side if the carrying capacity is a maximum.

Solution. The area of the cross section shown in the figure must be a maximum. The cross section is a trapezoid of upper base $24 - 2x + 2x \cos \alpha$, lower base $24 - 2x$, and altitude $x \sin \alpha$. The area A is given by



$$(5) \quad A = 24x \sin \alpha - 2x^2 \sin \alpha + x^2 \sin \alpha \cos \alpha.$$

By differentiation we have

$$\frac{\partial A}{\partial x} = 24 \sin \alpha - 4x \sin \alpha + 2x \sin \alpha \cos \alpha.$$

$$\frac{\partial A}{\partial \alpha} = 24x \cos \alpha - 2x^2 \cos \alpha + x^2(\cos^2 \alpha - \sin^2 \alpha).$$

Setting the partial derivatives equal to zero, we have the two equations

$$2 \sin \alpha(12 - 2x + x \cos \alpha) = 0.$$

$$x[24 \cos \alpha - 2x \cos \alpha + x(\cos^2 \alpha - \sin^2 \alpha)] = 0.$$

One solution of this system is $\alpha = 0$, $x = 0$, which has no meaning in the physical problem. Assuming $\alpha \neq 0$, $x \neq 0$, and solving the equations, we get $\cos \alpha = \frac{1}{2}$, $x = 8$.

A consideration of the physical problem shows that there must exist a maximum value of the area. Hence this maximum value occurs when $\alpha = 60^\circ$ and $x = 8''$.

We now establish a sufficient condition. Assuming that equations (3) hold, we obtain from (9), Art. 240, substituting $x_0 = a$, $y_0 = b$, and transposing,

$$(6) \quad f(a+h, b+k) - f(a, b) = \frac{1}{2} [h^2 f_{xx}(x, y) + 2hk f_{xy}(x, y) + k^2 f_{yy}(x, y)],$$

where we have set $x = a + \theta h$, $y = b + \theta k$. By (1) and (2), $f(a, b)$ will be a maximum (or a minimum) if the right-hand member is negative (or positive) for all values of h and k sufficiently small in numerical value (zero excluded). Set

$$(7) \quad A = f_{xx}(x, y), \quad B = f_{xy}(x, y), \quad C = f_{yy}(x, y),$$

and consider the identity

$$(8) \quad Ah^2 + 2Bhk + Ck^2 = \frac{1}{A} [(Ah + Bk)^2 + (AC - B^2)k^2].$$

The expression within the square brackets in the right-hand member in (8) is always positive if

$$(9) \quad AC - B^2 > 0,$$

and the left-hand member therefore has the same sign as A (or C , since, by (9), A and C must agree in sign). The question now is, therefore, to interpret the criterion (9) for the right-hand member in (6), in which, as already stated, h and k are numerically small. Assume that (9) holds when $x = a$, $y = b$. Then, the derivatives in (7) being continuous, it will hold also for values of x , y near a , b . Also, the sign of A (or C) will be the same as the sign of $f_{xx}(a, b)$ (or $f_{yy}(a, b)$). Thus we have established the following rule for finding maximum and minimum values of a function $f(x, y)$.

FIRST STEP. Solve the simultaneous equations

$$\frac{\partial f}{\partial x} = 0, \quad \frac{\partial f}{\partial y} = 0.$$

SECOND STEP. Calculate for these values of x and y the value of

$$\Delta = \frac{\partial^2 f}{\partial x^2} \frac{\partial^2 f}{\partial y^2} - \left(\frac{\partial^2 f}{\partial x \partial y} \right)^2.$$

THIRD STEP. The function will have

$$\text{a maximum value if } \Delta > 0 \quad \text{and} \quad \frac{\partial^2 f}{\partial x^2} \left(\text{or } \frac{\partial^2 f}{\partial y^2} \right) < 0;$$

$$\text{a minimum value if } \Delta > 0 \quad \text{and} \quad \frac{\partial^2 f}{\partial x^2} \left(\text{or } \frac{\partial^2 f}{\partial y^2} \right) > 0.$$

If Δ is negative, it is not difficult to see that $f(x, y)$ will have neither a maximum nor a minimum value.

The student should notice that this rule does not necessarily give all maximum and minimum values. For a pair of values of x and y determined by the First Step may cause Δ to vanish, and may lead to a maximum or a minimum or neither. Further investigation is therefore necessary for such values. The rule is, however, sufficient for solving many important examples.

The question of maxima and minima of functions of three or more independent variables must be left to more advanced treatises.

ILLUSTRATIVE EXAMPLE 2. Examine the function $3axy - x^3 - y^3$ for maximum and minimum values.

Solution.

$$f(x, y) = 3axy - x^3 - y^3.$$

$$\text{First Step.} \quad \frac{\partial f}{\partial x} = 3ay - 3x^2 = 0, \quad \frac{\partial f}{\partial y} = 3ax - 3y^2 = 0.$$

Solving these two simultaneous equations, we get

$$x = 0, \quad x = a,$$

$$y = 0, \quad y = a.$$

Second Step. $\frac{\partial^2 f}{\partial x^2} = -6x, \quad \frac{\partial^2 f}{\partial x \partial y} = 3a, \quad \frac{\partial^2 f}{\partial y^2} = -6y;$

$$\Delta = \frac{\partial^2 f}{\partial x^2} \frac{\partial^2 f}{\partial y^2} - \left(\frac{\partial^2 f}{\partial x \partial y} \right)^2 = 36xy - 9a^2.$$

Third Step. When $x = 0$ and $y = 0$, $\Delta = -9a^2$, and there can be neither a maximum nor a minimum at $(0, 0)$.

When $x = a$ and $y = a$, $\Delta = +27a^2$; and since $\frac{\partial^2 f}{\partial x^2} = -6a$, we have the conditions for a maximum value of the function fulfilled at (a, a) . Substituting $x = a$, $y = a$ in the given function, we get its maximum value equal to a^3 .

ILLUSTRATIVE EXAMPLE 3. Divide a into three parts such that their product shall be a maximum.

Solution. Let x = first part, y = second part; then $a - (x + y) = a - x - y$ = third part, and the function to be examined is

$$f(x, y) = xy(a - x - y).$$

First Step. $\frac{\partial f}{\partial x} = ay - 2xy - y^2 = 0, \quad \frac{\partial f}{\partial y} = ax - 2xy - x^2 = 0.$

Solving simultaneously, we get as one pair of values $x = \frac{a}{3}, y = \frac{a}{3}$.

Second Step. $\frac{\partial^2 f}{\partial x^2} = -2y, \quad \frac{\partial^2 f}{\partial x \partial y} = a - 2x - 2y, \quad \frac{\partial^2 f}{\partial y^2} = -2x;$

$$\Delta = 4xy - (a - 2x - 2y)^2.$$

Third Step. When $x = \frac{a}{3}$ and $y = \frac{a}{3}$, $\Delta = \frac{a^2}{3}$; and since $\frac{\partial^2 f}{\partial x^2} = -\frac{2a}{3}$, it is seen that our product is a maximum when $x = \frac{a}{3}, y = \frac{a}{3}$. Therefore the third part is also $\frac{a}{3}$, and the maximum value of the product is $\frac{a^3}{27}$.

PROBLEMS

Discuss for maxima and minima the following functions.

1. $x^2 + xy + y^2 - 6x + 2.$ *Ans.* $x = 4, y = -2$ gives min.

2. $4x + 2y - x^2 + xy - y^2.$ $x = \frac{1}{3}, y = \frac{8}{3}$ gives max.

3. $2x^2 - 2xy + y^2 + 5x - 3y.$ $x = -\frac{7}{2}, y = \frac{1}{2}$ gives min.

4. $x^3 - 3axy + y^3.$ $x = y = a$ gives min.

5. $\sin x + \sin y + \sin(x + y).$ $x = y = \frac{\pi}{3}$ gives max.

$x = y = \frac{5\pi}{3}$ gives min.

6. $x^2 - xy + y^2 + ax + by + c.$

7. $xy + \frac{a^3}{x} + \frac{b^3}{y}.$

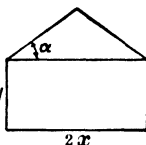
8. Show that the maximum value of $\frac{(ax + by + c)^2}{x^2 + y^2 + 1}$ is $a^2 + b^2 + c^2$.

9. Find the rectangular parallelepiped of maximum volume which has three faces in the coördinate planes and one vertex in the plane $\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1$. Ans. Volume = $\frac{abc}{27}$.

10. Find the volume of the largest rectangular parallelepiped that can be inscribed in the ellipsoid $\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$. Ans. $\frac{8abc}{3\sqrt{3}}$.

11. A pentagon is composed of a rectangle surmounted by an isosceles triangle. If the perimeter of the pentagon has a given value P , find the dimensions for maximum area.

$$\text{Ans. } \alpha = 30^\circ, \quad 2x = \frac{P}{2 + 2 \sec \alpha - \tan \alpha}, \quad y = \frac{P}{2} - x(1 + \sec \alpha).$$



12. Find the shortest distance between the lines $x = \frac{y}{2} = \frac{z}{3}$ and $x = y - 3 = z$.

13. A manufacturer produces two lines of candy at constant average costs of 50 cents and 60 cents per pound respectively. If the selling price of the first line is x cents per pound and of the second line is y cents per pound, the number of pounds which can be sold each week is given by the formulas $N_1 = 250(y - x)$, $N_2 = 32,000 + 250(x - 2y)$.

Show that for maximum profit the selling prices should be fixed at 89 cents and 94 cents per pound respectively.

14. A manufacturer produces razors and blades at a constant average cost of 40 cents per razor and 20 cents per dozen blades. If the razors are sold at x cents each and the blades at y cents per dozen, the demand of the market each week is $\frac{4,000,000}{xy}$ razors and $\frac{8,000,000}{xy}$ dozen blades. Find the selling prices for maximum profit.

242. Taylor's theorem for functions of two or more variables. The expansion of $f(x, y)$ is found by using the methods and results of Arts. 194 and 240. We consider

$$(1) \quad F(t) = f(x + ht, y + kt),$$

and expand $F(t)$ as in (5), Art. 194. The result is

$$(2) \quad F(t) = F(0) + F'(0) \frac{t}{1} + F''(0) \frac{t^2}{2} + \dots + F^{(n-1)}(0) \frac{t^{n-1}}{(n-1)} + R.$$

We obtain the values of $F(0)$, $F'(0)$, $F''(0)$, by substituting $t = 0$ in (2), (4), (7), Art. 240. By differentiating (7), and putting $t = 0$, the expressions for $F'''(0)$ etc. will result. These are omitted here. Note, however, that $F'''(0)$ is homogeneous and of the third degree

in h and k . A similar property holds for higher derivatives. If these values are substituted in (2), and we set $t = 1$, the result is

$$(3) \quad f(x+h, y+k) = f(x, y) + hf_x(x, y) + kf_y(x, y) \\ + \frac{1}{2} [h^2 f_{xx}(x, y) + 2hk f_{xy}(x, y) + k^2 f_{yy}(x, y)] + \cdots + R.$$

The expression for R is complicated and will be omitted from this point on.

In (3) write $x = a$, $y = b$, and then replace h by $(x - a)$ and k by $(y - b)$. The result is *Taylor's theorem for a function of two variables*,

$$(I) \quad f(x, y) = f(a, b) + f_x(a, b)(x - a) + f_y(a, b)(y - b) \\ + \frac{1}{2} [f_{xx}(a, b)(x - a)^2 + 2f_{xy}(a, b)(x - a)(y - b) \\ + f_{yy}(a, b)(y - b)^2] + \cdots.$$

Finally, setting $a = b = 0$, we obtain an expansion corresponding to Maclaurin's series (A), Art. 194,

$$(J) \quad f(x, y) = f(0, 0) + f_x(0, 0)x + f_y(0, 0)y \\ + \frac{1}{2} [f_{xx}(0, 0)x^2 + 2f_{xy}(0, 0)xy + f_{yy}(0, 0)y^2] + \cdots.$$

The right-hand member in (J) may be written as the infinite series

$$(4) \quad u_0 + \frac{u_1}{1} + \frac{u_2}{2} + \cdots,$$

where $u_0 = f(0, 0),$
 $u_1 = f_x(0, 0)x + f_y(0, 0)y,$
 $u_2 = f_{xx}(0, 0)x^2 + 2f_{xy}(0, 0)xy + f_{yy}(0, 0)y^2,$
 etc.

These terms in (4) are homogeneous polynomials in (x, y) . The degree of each is equal to the subscript. That is, by (J) the function is expanded into a sum of polynomials homogeneous in (x, y) and of ascending degree. Similarly, in (I) the terms in the expansion are polynomials homogeneous in $(x - a, y - b)$.

Formula (I) is called *the expansion of $f(x, y)$ at the point (a, b)* .

Reference must be made to more advanced treatises for proof of the problem of determining those values of (x, y) for which the expansions (I) and (J) hold.

By breaking off series (4) at any term, an approximate formula for $f(x, y)$ is obtained for values near (a, b) or $(0, 0)$. Compare Art. 200.

ILLUSTRATIVE EXAMPLE. Expand

$$xy^2 + \sin xy$$

at the point $(1, \frac{1}{2}\pi)$ up to terms of the third degree.

Solution. Here
and

$$a = 1, b = \frac{1}{2}\pi,$$

$$f(x, y) = xy^2 + \sin xy,$$

$$f_x(x, y) = y^2 + y \cos xy,$$

$$f_y(x, y) = 2xy + x \cos xy,$$

$$f_{xx}(x, y) = -y^2 \sin xy,$$

$$f_{xy}(x, y) = 2y + \cos xy - xy \sin xy,$$

$$f_{yy}(x, y) = 2x - x^2 \sin xy.$$

Substituting $x = 1, y = \frac{1}{2}\pi$, the results are

$$f(1, \frac{1}{2}\pi) = \frac{1}{4}\pi^2 + 1,$$

$$f_x(1, \frac{1}{2}\pi) = \frac{1}{4}\pi^2,$$

$$f_y(1, \frac{1}{2}\pi) = \pi,$$

$$f_{xx}(1, \frac{1}{2}\pi) = -\frac{1}{4}\pi^2,$$

$$f_{xy}(1, \frac{1}{2}\pi) = \frac{1}{2}\pi,$$

$$f_{yy}(1, \frac{1}{2}\pi) = 1.$$

Substituting in (I), we get

$$\begin{aligned} xy^2 + \sin xy = & 1 + \frac{1}{4}\pi^2 + \frac{1}{4}\pi^2(x-1) + \pi(y - \frac{1}{2}\pi) \\ & + \frac{1}{2}\left[-\frac{1}{4}\pi^2(x-1)^2 + \pi(x-1)\left(y - \frac{1}{2}\pi\right) + \left(y - \frac{1}{2}\pi\right)^2\right] + \dots \text{Ans.} \end{aligned}$$

Formulas for expanding a function of three variables $f(x, y, z)$ are readily derived, and are left as problems.

PROBLEMS

1. From (1) above, show that

$$F'''(0) = h^3 \left| \frac{\partial^3 f}{\partial x^3} \right|_0 + 3 h^2 k \left| \frac{\partial^3 f}{\partial x^2 \partial y} \right|_0 + 3 h k^2 \left| \frac{\partial^3 f}{\partial x \partial y^2} \right|_0 + k^3 \left| \frac{\partial^3 f}{\partial y^3} \right|_0.$$

2. Verify the following expansion.

$$\begin{aligned} \cos x \cos y = & 1 - \frac{x^2 + y^2}{\frac{1}{2}} + \frac{x^4 + 6x^2y^2 + y^4}{\frac{1}{4}} \\ & - \frac{x^6 + 15x^4y^2 + 15x^2y^4 + y^6}{\frac{1}{6}} + \dots \end{aligned}$$

3. Expand $\sin x \sin y$ in powers of x and y .

4. Verify the following expansion.

$$a^x \log(1+y) = y + \frac{1}{2}(2xy \log a - y^2 + x^2y \log^2 a - xy^2 \log a) + \frac{1}{3}y^3 + \dots$$

5. Expand $x^3 + xy^2$ at the point $(1, 2)$.

6. Verify the following expansion.

$$\sin(x+y) = x + y - \frac{x^3 + 3x^2y + 3xy^2 + y^3}{\frac{1}{3}} + \dots$$

Verify the following approximate formulas for small values of x and y .

7. $e^x \sin y = y + xy.$

9. $\sqrt{\frac{1+x}{1+y}} = 1 + \frac{1}{2}(x-y).$

8. $e^x \ln(1+y) = y + ry$

CHAPTER XXV

MULTIPLE INTEGRALS

243. Partial and successive integration. Corresponding to *partial differentiation* in the differential calculus we have the inverse process of *partial integration* in the integral calculus. As may be inferred from the connection, partial integration means that, having given a differential expression involving two or more independent variables, we integrate it, considering first *a single one only* as varying and all the rest constant. Then we integrate the result, considering another one as varying and the others constant, and so on. Such integrals are called *double, triple*, etc., according to the number of variables, and are known as *multiple integrals*.

In the solution of this problem the only new feature is that the constant of integration has a new form. We shall illustrate this by means of examples. Thus, suppose we wish to find u , having given

$$\frac{\partial u}{\partial x} = 2x + y + 3.$$

Integrating this with respect to x , considering y as constant, we have

$$u = x^2 + xy + 3x + \phi,$$

where ϕ denotes the constant of integration. But since y was regarded as constant during this integration, ϕ may involve y . We shall then indicate this dependence of ϕ on y by replacing ϕ by the symbol $\phi(y)$. Hence the most general form of u is

$$u = x^2 + xy + 3x + \phi(y),$$

where $\phi(y)$ denotes an arbitrary function of y .

As another problem let us find

$$u = \iint (x^2 + y^2) dy dx.$$

This means that we wish to find u , having given

$$\frac{\partial^2 u}{\partial x \partial y} = x^2 + y^2.$$

Integrating first with respect to y , regarding x as constant, we get

$$\frac{\partial u}{\partial x} = x^2y + \frac{y^3}{3} + \psi(x),$$

where $\psi(x)$ is an arbitrary function of x .

Now integrating this result with respect to x , regarding y as constant, we have

$$u = \frac{x^3y}{3} + \frac{xy^3}{3} + \Psi(x) + \Phi(y),$$

where $\Phi(y)$ is an arbitrary function of y , and

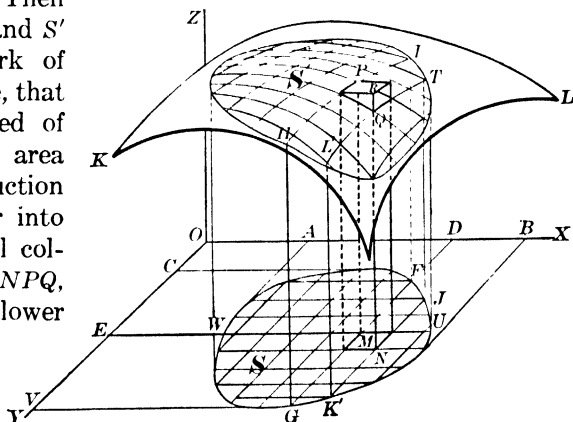
$$\Psi(x) = \int \psi(x) dx.$$

244. Definite double integral. Geometric interpretation. Let $f(x, y)$ be a continuous and single-valued function of x and y . Geometrically,

$$(1) \quad z = f(x, y)$$

is the equation of a surface, as KL . Take some area S in the XOY -plane and construct upon S as a base the right cylinder whose elements are parallel to OZ . Let this cylinder inclose the area S' on KL . Let us now find the volume V of the solid bounded by S , S' , and the cylindrical surface. We proceed as follows:

At equal distances apart ($= \Delta x$) in the area S draw a set of lines parallel to OY , and then a second set parallel to OX at equal distances apart ($= \Delta y$). Through these lines pass planes parallel to YOZ and XOZ respectively. Then within the areas S and S' we have a network of lines, as in the figure, that in S being composed of rectangles, each of area $\Delta x \Delta y$. This construction divides the cylinder into a number of vertical columns, such as $MNPQ$, whose upper and lower bases are corresponding portions of the networks in S' and S respectively. As the upper bases of these columns are curvilinear, we of course cannot calculate the volume of the columns directly. Let



us replace these columns by prisms whose upper bases are found thus: each column is cut through by a plane parallel to XOY passed through that vertex of the upper base for which x and y have the least numerical values. Thus the column $MNPQ$ is replaced by the right prism $MNPR$, the upper base being in a plane through P parallel to the XOY -plane.

If the coördinates of P are (x, y, z) , then $MP = z = f(x, y)$, and therefore

$$(2) \quad \text{Volume of } MNPR = f(x, y) \Delta y \Delta x.$$

Calculating the volume of each of the other prisms formed in the same way by replacing x and y in (2) by corresponding values, and adding the results, we obtain a volume V' approximately equal to V ; that is,

$$(3) \quad V' = \sum \sum f(x, y) \Delta y \Delta x;$$

where the double summation sign $\sum \sum$ indicates that values of *two variables* x, y must be taken account of in the quantity to be summed up.

If now in the figure we increase the number of divisions of the network in S indefinitely by letting Δx and Δy diminish indefinitely, and calculate in each case the double sum (3), then obviously V' will approach V as a limit, and hence we have the fundamental result

$$(4) \quad V = \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \sum \sum f(x, y) \Delta y \Delta x.$$

We show now that this limit can be found by successive integration.

The required volume may be found as follows: Consider any one of the slices into which the solid is divided by two successive planes parallel to YOZ ; for example, the slice whose faces are $FIHG$ and $JTL'K'$. The thickness of this slice is Δx . Now the values of z along the curve HI are found by writing $x = OD$ in the equation $z = f(x, y)$; that is, along HI

$$z = f(OD, y).$$

$$\text{Hence} \quad \text{Area } FIHG = \int_{DF}^{DG} f(OD, y) dy.$$

The volume of the slice under discussion is approximately equal to that of a prism with base $FIHG$ and altitude Δx ; that is, equal to

$$\Delta x \cdot \text{area } FIHG = \Delta x \int_{DF}^{DG} f(OD, y) dy.$$

The required volume of the whole solid is evidently the limit of the sum of all prisms constructed in like manner, as $x (= OD)$ varies from OA to OB ; that is,

$$(5) \quad V = \int_{OA}^{OB} dx \int_{DF}^{DG} f(x, y) dy.$$

Similarly, it may be shown that

$$(6) \quad V = \int_{OC}^{OV} dy \int_{EW}^{EU} f(x, y) dx.$$

The integrals (5) and (6) are also written in the more compact form

$$\int_{OA}^{OB} \int_{DF}^{DG} f(x, y) dy dx \quad \text{and} \quad \int_{OC}^{OV} \int_{EW}^{EU} f(x, y) dx dy.$$

In (5) the limits DF and DG are functions of x , since they are found by solving the equation of the boundary curve of the base of the solid for y .

Similarly, in (6) the limits EW and EU are functions of y . Now comparison of (4), (5), and (6) gives the result

$$\begin{aligned} (A) \quad V &= \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \sum \sum f(x, y) \Delta y \cdot \Delta x = \int_{a_2}^{a_1} \int_{u_2}^{u_1} f(x, y) dy dx \\ &= \int_{b_2}^{b_1} \int_{v_2}^{v_1} f(x, y) dx dy, \end{aligned}$$

where v_1 and v_2 are, in general, functions of y , and u_1 and u_2 functions of x . The second integral sign in each case applies to the first differential.

Equation (A) is an extension of the Fundamental Theorem of Art. 156 to double sums.

Our result may be stated in the following form.

The definite double integral

$$\int_{a_2}^{a_1} \int_{u_2}^{u_1} f(x, y) dy dx$$

may be interpreted as that portion of the volume of a right cylinder which is included between the plane XOY and the surface

$$z = f(x, y),$$

the base of the cylinder being the area in the XOY-plane bounded by the curves

$$y = u_1, \quad y = u_2, \quad x = a_1, \quad x = a_2.$$

A similar statement holds for the second integral.

It is instructive to look upon the above process of finding the volume of the solid as follows.

Consider a column with rectangular base $dy\,dx$ and of altitude z as an element of the volume. Summing up all such elements from $y = DF$ to $y = DG$, x in the meanwhile being constant (say $= OD$), gives the volume of a thin slice having $FGHI$ as one face. The volume of the whole solid is then found by summing up all such slices from $x = OA$ to $x = OB$.

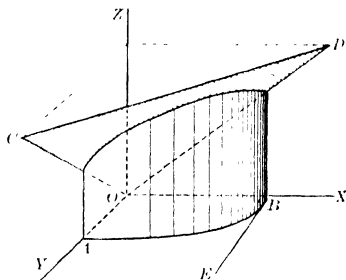
In successive integration involving two variables the order of integration denotes that the limits on the second integral sign correspond to the variable whose differential is written first, the differentials of the variables and their corresponding limits being written in the reverse order. Before attempting to apply successive integration to practical problems it is best that the student should acquire by practice some facility in evaluating definite multiple integrals.

ILLUSTRATIVE EXAMPLE 1. Find the value of the definite double integral

$$\int_0^a \int_0^{\sqrt{a^2-x^2}} (x+y) dy\,dx.$$

Solution. $\int_0^a \int_0^{\sqrt{a^2-x^2}} (x+y) dy\,dx$

$$\begin{aligned} &= \int_0^a \left[\int_0^{\sqrt{a^2-x^2}} (x+y) dy \right] dx \\ &= \int_0^a \left[xy + \frac{y^2}{2} \right]_0^{\sqrt{a^2-x^2}} dx \\ &= \int_0^a \left(x\sqrt{a^2-x^2} + \frac{a^2-x^2}{2} \right) dx \\ &= \frac{2}{3} \frac{a^3}{3}. \quad \text{Ans.} \end{aligned}$$



Interpreting this result geometrically, we have found the volume of the solid of cylindrical shape standing on OAB as base and bounded at the top by the surface (plane) $z = x + y$.

The solid here stands on a base in the XOY -plane bounded by

$$\left. \begin{aligned} y &= 0 \text{ (line } OB) \\ y &= \sqrt{a^2-x^2} \text{ (quadrant of circle } AB) \\ x &= 0 \text{ (line } OA) \\ x &= a \text{ (line } BE) \end{aligned} \right\} \begin{aligned} &\text{from } y \text{ limits;} \\ &\text{from } x \text{ limits.} \end{aligned}$$

ILLUSTRATIVE EXAMPLE 2. Verify $\int_b^{2b} \int_0^a (a-y)x^2 dy\,dx = \frac{7}{6} \frac{a^2 b^3}{6}$.

Solution. $\int_b^{2b} \int_0^a (a-y)x^2 dy\,dx = \int_b^{2b} \left[ay - \frac{y^2}{2} \right]_0^a x^2 dx = \int_b^{2b} \frac{a^2}{2} x^2 dx = \frac{7}{6} \frac{a^2 b^3}{6}$.

ILLUSTRATIVE EXAMPLE 3. Verify $\int_0^a \int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} x\,dy\,dx = \frac{2}{3} \frac{a^3}{3}$.

Solution. $\int_0^a \int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} x\,dy\,dx = \int_0^a \left[xy \right]_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} dx$
 $= \int_0^a 2x\sqrt{a^2-x^2} dx = \left[-\frac{2}{3} (a^2-x^2)^{\frac{3}{2}} \right]_0^a = \frac{2}{3} \frac{a^3}{3}.$

In successive integration involving three variables the order of integration is denoted in the same way as for two variables; that is, the order of the limits on the integral signs, reading from the inside to the left, is the same as the order of the corresponding variables whose differentials are read from the inside to the right.

ILLUSTRATIVE EXAMPLE 4. Verify $\int_2^3 \int_1^2 \int_2^5 xy^2 dz dy dx = \frac{35}{2}$.

$$\begin{aligned} \text{Solution. } \int_2^3 \int_1^2 \int_2^5 xy^2 dz dy dx &= \int_2^3 \int_1^2 \left[\int_2^5 xy^2 dz \right] dy dx = \int_2^3 \int_1^2 \left[xy^2 z \right]_2^5 dy dx \\ &= 3 \int_2^3 \int_1^2 xy^2 dy dx = 3 \int_2^3 \left[\int_1^2 xy^2 dy \right] dx \\ &= 3 \int_2^3 \left[\frac{xy^3}{3} \right]_1^2 dx = 7 \int_2^3 x dx = \frac{35}{2}. \end{aligned}$$

In Problems 1-10 in the following list the solid whose volume equals the value of the integral should be described.

PROBLEMS

Work out the following definite integrals.

$$1. \int_0^1 \int_0^2 (x+2) dy dx = 5.$$

$$6. \int_1^2 \int_y^{y^2} (x+2y) dx dy = \frac{13}{30}.$$

$$2. \int_0^4 \int_0^x y dy dx = \frac{32}{3}.$$

$$7. \int_0^1 \int_{y+1}^{2y} xy dx dy = \frac{1}{24}.$$

$$3. \int_0^a \int_0^{\sqrt{x}} dy dx = \frac{2}{3} a^{\frac{3}{2}}.$$

$$8. \int_1^4 \int_0^{\sqrt{x}} (x+y) dy dx = \frac{1}{5}.$$

$$4. \int_1^2 \int_0^{\frac{y}{2}} y dx dy = \frac{7}{6}.$$

$$9. \int_0^2 \int_0^x (x^2 + y^2) dy dx = \frac{16}{3}.$$

$$5. \int_0^2 \int_0^{x^2} y dy dx = \frac{16}{5}.$$

$$10. \int_0^1 \int_0^{\sqrt{y}} e^{\frac{y}{x}} dy dx = \frac{1}{2}.$$

$$11. \int_b^a \int_{\beta}^{\alpha} \rho^2 \sin \theta d\theta d\rho = \frac{1}{3} (a^3 - b^3) (\cos \beta - \cos \alpha).$$

$$12. \int_0^{\pi} \int_0^{a \cos \theta} \rho \sin \theta d\rho d\theta = \frac{1}{3} a^2.$$

$$13. \int_0^{\pi} \int_0^{a(1 + \cos \theta)} \rho^2 \sin \theta d\rho d\theta = \frac{1}{3} a^3.$$

$$14. \int_0^{\frac{\pi}{2}} \int_{a \cos \theta}^a \rho^4 d\rho d\theta = \left(\pi - \frac{1}{5} \right) \frac{a^5}{10}.$$

$$15. \int_b^a \int_0^b \int_a^{2a} x^2 y^2 z dz dy dx = \frac{1}{6} a^2 b^4 (a^3 - b^3).$$

$$16. \int_0^a \int_0^x \int_0^y x^2 y^2 z dz dy dx = \frac{1}{90} a^9.$$

$$17. \int_0^1 \int_y^1 \int_0^{1-x} x \, dz \, dx \, dy = \frac{1}{35}.$$

$$18. \int_0^1 \int_0^{1-x} \int_0^{1-y} z \, dz \, dy \, dx = \frac{1}{60}.$$

$$19. \int_1^2 \int_0^z \int_0^{x/3} \left(\frac{x}{x^2 + y^2} \right) dy \, dx \, dz = \frac{1}{2} \pi.$$

$$20. \int_0^1 \int_0^x \int_0^{x+y} e^{x+y+z} dz \, dy \, dx = \frac{1}{8} e^4 - \frac{3}{4} e^2 + e - \frac{3}{8}.$$

245. Value of a definite double integral taken over a region S . In the last article the definite double integral appeared as a volume. This does not necessarily mean that every definite double integral is a volume, for the physical interpretation of the result depends on the nature of the quantities represented by x , y , z . If x , y , z are the coordinates of a point in space, then the result is indeed a volume. In order to give the definite double integral in question an interpretation not necessarily involving the geometric concept of volume, we observe that the variable z does not occur explicitly in the integral, and therefore we may confine ourselves to the XOY -plane. In fact, let us consider simply a region S in the XOY -plane, and a given function $f(x, y)$. Within this region construct rectangular elements of area by drawing a network of lines, as in Art. 244. Choose a point (x, y) of the rectangular element of area $\Delta x \, \Delta y$, either within the rectangle or on its perimeter. Form the product

$$f(x, y) \Delta x \, \Delta y,$$

and similar products for all other rectangular elements. Sum up these products. The result is

$$\sum \sum f(x, y) \Delta x \, \Delta y.$$

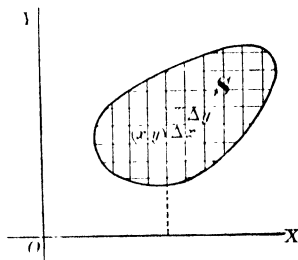
Finally let $\Delta x \rightarrow 0$, and $\Delta y \rightarrow 0$.

We write the result

$$(1) \quad \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \sum \sum f(x, y) \Delta x \, \Delta y = \iint_S f(x, y) dx \, dy,$$

and call it the double integral of the function $f(x, y)$ taken over the region S .

By (A) the value of the left-hand member in (1) was found by successive integration when $f(x, y)$ had no negative values for the region S . The reasoning of Art. 244 will hold, however, if the portion



S' of the surface $z = f(x, y)$ lies below the plane XOY . The limit of the double sum will then be the volume with a negative sign. The integrals in (A) will give the same negative number. Finally, if $f(x, y)$ is sometimes positive, sometimes negative for points of S , we may divide S into subregions in which $f(x, y)$ will be either always positive or always negative. The reasoning will hold for each subregion and therefore for the combined region S . Hence the conclusion: *the double integral in (1) may be evaluated in all cases by successive integration.*

It remains to explain the method of determining the *limits* of integration. This is done in the next article.

246. Plane area as a definite double integral. Rectangular coördinates. The problem of plane areas has been solved by single integration in Art. 145. The discussion using double integration is useful chiefly because the determination of limits for the general problem of Art. 245 is made clear. To set up the desired double integral, proceed as follows.

Draw a network of rectangles as before. Then, in the figure,

$$(1) \quad \text{Element of area} = \Delta x \Delta y.$$

If A is the entire area of the region S , obviously, by (1), Art. 245,

$$(B) \quad A = \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \sum \sum \Delta x \Delta y = \iint_S dx dy.$$

Referring to the result stated in Art. 245, we may say:

The area of any region is the value of the double integral of the function $f(x, y) = 1$ taken over that region.

Or, also: *The area equals numerically the volume of a right cylinder of unit height erected on the base S . (Art. 244.)*

The examples show how the limits of integration are found.

ILLUSTRATIVE EXAMPLE 1. Calculate that portion of the area above OX which is bounded by the semicubical parabola $y^2 = x^3$ and the straight line $y = x$.

Solution. The order of integration is indicated in the figure. Integrate first with respect to x . That is, sum up first the elements $dx dy$ in a horizontal strip. Then we have

$$\int_{AB}^{AC} dx dy = dy \int_{AB}^{AC} dx = \text{area of a horizontal strip of altitude } dy.$$

Next, integrate this result with respect to y . This corresponds to summing up all horizontal strips. In this way we obtain

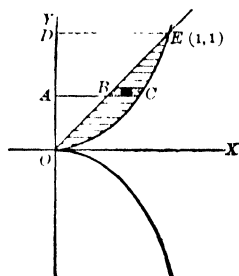
$$A = \int_0^{OD} \int_{AB}^{AC} dx dy.$$

The limits AB and AC are found by solving each of the equations of the bounding curves for x . Thus from the equation of the line, $x = AB = y$, and from the equation of the curve, $x = AC = y^{\frac{2}{3}}$. To determine OD , solve the two equations *simultaneously* to find the point of intersection E . This gives the point $(1, 1)$; hence $OD = 1$. Therefore

$$A = \int_0^1 \int_y^{y^{\frac{2}{3}}} dx dy = \int_0^1 (y^{\frac{2}{3}} - y) dy = \left[\frac{3}{5} y^{\frac{5}{3}} - \frac{1}{2} y^2 \right]_0^1 = \frac{3}{5} - \frac{1}{2} = \frac{1}{10}. \text{ Ans.}$$

Or we may begin by summing up the elements $dx dy$ in a vertical strip, and then sum up these strips. We shall then have

$$A = \int_0^1 \int_{x^{\frac{3}{2}}}^x dy dx = \int_0^1 (x - x^{\frac{3}{2}}) dx = \frac{1}{2} - \frac{2}{5} = \frac{1}{10}.$$



In this example either order of integration may be chosen. This is not always the case, as the following example shows.

ILLUSTRATIVE EXAMPLE 2. Find the area in the first quadrant bounded by the x -axis and the curves $x^2 + y^2 = 10$, $y^2 = 9x$.

Solution. Here we first integrate with respect to x to cover a horizontal strip, that is, from the parabola to the circle. We then have, for the entire area,

$$A = \int_0^3 \int_{HG}^{HI} dx dy,$$

since the point of intersection S is $(1, 3)$. To find HG , solve $y^2 = 9x$ for x . Then

$$x = HG = \frac{1}{9} y^2.$$

To find HI , solve $x^2 + y^2 = 10$ for x . We get

$$x = HI = +\sqrt{10 - y^2}.$$

Hence

$$A = \int_0^3 \int_{\frac{1}{9}y^2}^{\sqrt{10-y^2}} dx dy = \left[\frac{y}{2} \sqrt{10-y^2} + 5 \arcsin \frac{y}{\sqrt{10}} - \frac{1}{27} y^3 \right]_0^3 = 6.75. \text{ Ans.}$$

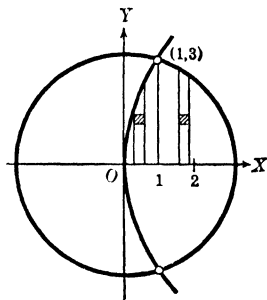
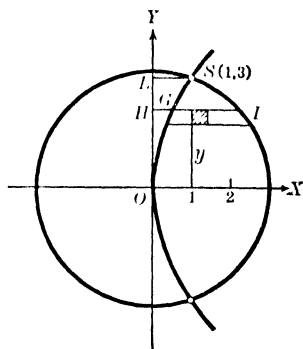
If we integrate first with respect to y , using vertical strips, two integrals are necessary. Then

$$A = \int_0^1 \int_0^{\sqrt{9x}} dy dx + \int_1^{\sqrt{10}} \int_0^{\sqrt{10-x^2}} dy dx = 6.75.$$

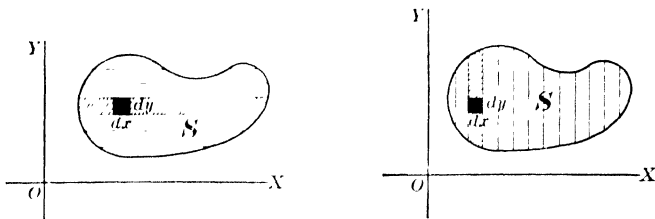
The order of integration should be such that the area is given by one integral, if this is possible.

The examples above show that we set

$$A = \iint dx dy \quad \text{or} \quad A = \iint dy dx$$



according to the nature of the curves bounding the area. The figures below illustrate, in a general way, the difference in the summation processes indicated by the two integrals.



PROBLEMS

1. Find by double integration the area between the two parabolas $3y^2 = 25x$ and $5x^2 = 9y$, (a) by integrating first with respect to y ; (b) by integrating first with respect to x .

$$\text{Ans. (a) } \int_0^3 \int_{\frac{5x^2}{9}}^{\sqrt{\frac{25x}{3}}} dy dx = 5; \quad \text{(b) } \int_0^5 \int_{\frac{3y}{25}}^{\sqrt{\frac{9y}{5}}} dx dy = 5.$$

Calculate by double integration the finite area bounded by each of the following pairs of curves.

- | | |
|---|---|
| 2. $y = 4x - x^2$, $y = x$. | Ans. $4\frac{1}{2}$. |
| 3. $y^2 = 4x$, $2x - y = 4$. | 9. |
| 4. $y = x^2$, $2x - y + 3 = 0$. | $\frac{32}{3}$. |
| 5. $y^2 = 2x$, $x^2 = 6y$. | 4. |
| 6. $y^2 = 4x$, $x = 12 + 2y - y^2$. | $40\frac{2}{5}$. |
| 7. $y^2 = 2x$, $x^2 + y^2 = 4x$. | $\pi - \frac{8}{3}$. |
| 8. $y^2 = 9 + x$, $y^2 = 9 - 3x$. | 48. |
| 9. $(x^2 + 4a^2)y = 8a^3$, $2y = x$, $x = 0$. | $a^2(\pi - 1)$. |
| 10. $x^{\frac{1}{2}} + y^{\frac{1}{2}} = a^{\frac{1}{2}}$, $x + y = a$. | $\frac{1}{3}a^2$. |
| 11. $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$, $x + y = a$. | $\frac{1}{32}(16 - 3\pi)a^2$. |
| 12. $y = x^3 - 2x$, $y = 6x - x^3$. | 16. |
| 13. $x = 6y - y^2$, $y = x$. | 16. $x^2 + y^2 = 25$, $27y^2 = 16x^3$. |
| 14. $4y^2 = x^3$, $y = x$. | 17. $(2a - x)y^2 = x^3$, $y^2 = ax$. |
| 15. $y^2 = x + 4$, $y^2 = 4 - 2x$. | 18. $x^2 - y^2 = 14$, $x^2 + y^2 = 36$. |

247. Volume under a surface. In Art 244 we discussed the volume of a solid bounded by a surface

$$(1) \quad z = f(x, y),$$

the XOY -plane, and a cylinder. The elements of the cylinder were parallel to OZ , and its base was a region S in the XOY -plane. The volume of this solid is, by (A),

$$(2) \quad V = \iint_S z \, dx \, dy = \iint_S f(x, y) \, dx \, dy.$$

The order of integration and the limits are the same as for the area of the region S . The volume of a solid of this type is the "volume under the surface (1)." The analogous problem for the plane, "area under a curve," has been treated in Chapter XIV. As a special case the volume may be bounded by the surface and the XOY -plane itself.

Note that the element of volume in (2) is a right prism with base $dx \, dy$ and altitude z .

ILLUSTRATIVE EXAMPLE 1. Find the volume bounded by the elliptic paraboloid

$$(3) \quad 4z = 16 - 4x^2 - y^2$$

and the XOY -plane.

Solution. Solving (3) for z , we get

$$(4) \quad z = 4 - x^2 - \frac{1}{4}y^2.$$

Letting $z = 0$, we obtain

$$(5) \quad 4x^2 + y^2 = 16,$$

which is the equation of the perimeter of the base of the solid in the XOY -plane. Hence by (2), using the value of z in (4),

$$(6) \quad V = 4 \int_0^2 \int_0^{\sqrt{4-x^2}} (4 - x^2 - \frac{1}{4}y^2) \, dy \, dx = 16\pi. \text{ Ans.}$$

The limits are taken for the area OAB of the ellipse (5) lying in the first quadrant.

ILLUSTRATIVE EXAMPLE 2. Find the volume of the solid bounded by the paraboloid of revolution

$$(7) \quad x^2 + y^2 = az,$$

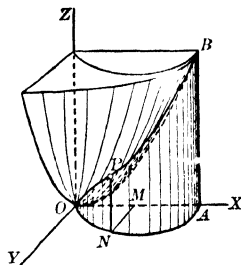
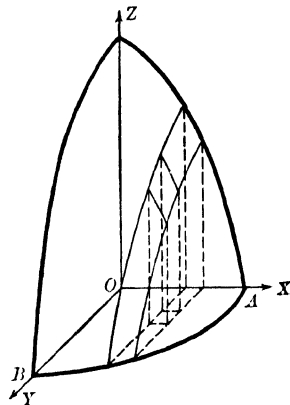
the XOY -plane, and the cylinder

$$(8) \quad x^2 + y^2 = 2ax.$$

Solution. Solving (7) for z , and finding the limits for the area of the base of the cylinder (8) in the XOY -plane, we get, using (2),

$$V = 2 \int_0^{2a} \int_0^{\sqrt{2ax-x^2}} \frac{x^2 + y^2}{a} \, dy \, dx = \frac{3}{2} \pi a^3. \text{ Ans.}$$

For the area ONA (see figure), $MN = \sqrt{2ax - x^2}$, (solving (8) for y), and $OA = 2a$. These are the limits.



PROBLEMS

1. Find the volume under $z = 4 - x^2$, above $z = 0$, and within $y^2 = 4x$.

$$\text{Ans. } V = 2 \int_0^2 \int_0^{2\sqrt{x}} (4 - x^2) dy dx = 17.24.$$

2. Find the volume under the plane $x + z = 2$, above $z = 0$, and within $x^2 + y^2 = 4$.

$$\text{Ans. } V = 2 \int_{-2}^2 \int_0^{2-x} (2 - x) dy dx = 8\pi.$$

3. Find the volume bounded by the plane $\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1$ and the co-ordinate planes.

$$\text{Ans. } \frac{1}{6} abc.$$

4. Find the volume bounded above by $x + z = 4$, below by $z = 0$, and laterally by $y^2 = 4x$.

$$\text{Ans. } \frac{5}{15} \pi^2.$$

5. Find the volume of the solid bounded above by $y^2 = a^2 - az$, below by $z = 0$, and within $x^2 + y^2 = a^2$.

$$\text{Ans. } \frac{3}{4} \pi a^3.$$

6. Find the volume under the elliptic paraboloid $z = 1 - \frac{1}{3}x^2 - \frac{1}{9}y^2$ and above $z = 0$.

$$\text{Ans. } 3\pi.$$

7. Find the volume under the plane $x + y + z = 8$, above $z = 0$, and between the planes $x + 2y = 8$, $x - 2y = 8$.

$$\text{Ans. } 170\frac{2}{3}.$$

8. Find the volume bounded by the cylindrical surface $x^2 + az = a^2$ and the planes $x + y = a$, $y = 0$, $z = 0$.

$$\text{Ans. } \frac{1}{3} a^3.$$

9. A solid is bounded by the surfaces $y^2 + z^2 = 4ax$, $x = 3a$, and lies within $y^2 = ax$. Find the volume.

$$\text{Ans. } (6\pi + 9\sqrt{3})a^3.$$

10. Find the volume below the cylindrical surface $y^2 = a^2 - az$, above $z = 0$, and within the cylindrical surface $x^2 + y^2 = ax$.

$$\text{Ans. } \frac{1}{64} \pi a^3.$$

11. Find the volume below $z = 2x + a$, above $z = 0$, and within $x^2 + y^2 = 2ax$.

$$\text{Ans. } 3\pi a^3.$$

12. Find the volume under $y^2 + z = 4$, above $z = 0$, and within the cylindrical surfaces $y^2 - 2x = 0$, $y^2 = 8 - 2x$.

$$\text{Ans. } \frac{5}{15} \pi^2.$$

13. A solid is bounded by the paraboloid $x^2 + y^2 = az$, the cylindrical surface $y^2 = a^2 - ax$, and the planes $x = 0$, $z = 0$. Find the volume.

$$\text{Ans. } \frac{4}{3} a^3.$$

14. Find the volume under $4z = 16 - 4x^2 - y^2$, above $z = 0$, and within $x^2 + y^2 = 2x$.

$$\text{Ans. } \frac{4}{16} \pi.$$

15. The axes of two circular cylindrical surfaces intersect at right angles and their radii are equal ($= r$). Find the common volume.

$$\text{Ans. } \frac{1}{3} \pi r^3.$$

16. Find the volume of the closed surface $x^{\frac{2}{3}} + y^{\frac{2}{3}} + z^{\frac{2}{3}} = a^{\frac{2}{3}}$. (The trace on each co-ordinate plane is the astroid, Chapter XXVI.)

$$\text{Ans. } \frac{4}{15} \pi a^3.$$

17. Find the volume common to $y^2 + z^2 = 4ax$ and $x^2 + y^2 = 2ax$.

$$\text{Ans. } (2\pi + \frac{1}{3}\pi^2)a^3.$$

248. Directions for setting up a double integral. We shall now state a rule for forming the double integral which will give a required property. Applications are made in the following articles. For single integration the corresponding rule is given in Art. 156.

FIRST STEP. Draw the curves which bound the region, or area, concerned.

SECOND STEP. At any point $P(x, y)$ within the area construct the rectangular element of area $\Delta x \Delta y$.

THIRD STEP. Work out the function $f(x, y)$, which, when multiplied by $\Delta x \Delta y$, gives the required property for the rectangular element of area.

FOURTH STEP. The required integral is

$$\iint f(x, y) dx dy$$

taken over the given region, or area. The order of integration and limits are determined in the same manner as in finding the area itself.

249. Moment of area and centroids. This problem is treated in Art. 177 by single integration. Double integration is often more convenient.

We follow the rule of the preceding article. The moments of area for the rectangular element of area are, respectively,

$x \Delta x \Delta y$, with respect to OY ,

$y \Delta x \Delta y$, with respect to OX .

Hence for the entire area, using the notation of Art. 177, we have

$$(C) \quad M_x = \iint y dx dy, \quad M_y = \iint x dx dy.$$

The centroid of the area is given by

$$(D) \quad \bar{x} = \frac{M_y}{\text{area}}, \quad \bar{y} = \frac{M_x}{\text{area}}.$$

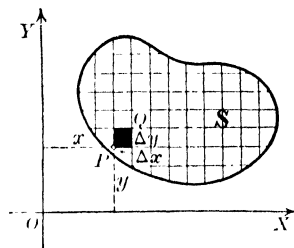
In (C) the integrals give the values of the double integrals of the functions

$$f(x, y) = y \quad \text{and} \quad f(x, y) = x,$$

respectively, taken over the area. (Art. 245.)

For an area bounded by a curve, the x -axis, and two ordinates (the "area under a curve"), we derive from (C)

$$(1) \quad \begin{aligned} M_x &= \int_a^b \int_0^y y dy dx = \frac{1}{2} \int_a^b y^2 dx, \\ M_y &= \int_a^b \int_0^y x dy dx = \int_a^b xy dx. \end{aligned}$$



These agree with (2), Art. 177. Note that y in (1) is the ordinate of a point on the curve, and its value in terms of x must be found from the equation of the curve and substituted in the integrand before integration.

ILLUSTRATIVE EXAMPLE. Find the centroid of the area in the first quadrant bounded by the semicubical parabola $y^2 = x^3$ and the straight line $y = x$.

Solution. The order and the limits of integration were found in Illustrative Example 1, Art. 246. Hence, using (C),

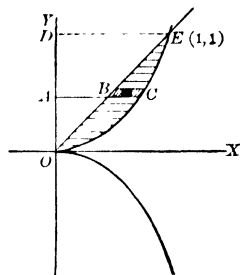
$$M_x = \int_0^1 \int_y^{\sqrt[3]{y}} y \, dx \, dy = \int_0^1 (y^{\frac{5}{3}} - y^2) dy = \frac{1}{24}.$$

$$M_y = \int_0^1 \int_y^{\sqrt[3]{y}} x \, dx \, dy = \frac{1}{2} \int_0^1 (y^{\frac{4}{3}} - y^2) dy = \frac{1}{24}.$$

Since

$$A = \text{area} = \frac{1}{10},$$

we have, from (D), $\bar{x} = \frac{1}{10} \cdot \frac{1}{24} = 0.48$, $\bar{y} = \frac{1}{10} \cdot \frac{1}{24} = 0.42$. Ans.



250. Theorem of Pappus. A useful relation between centroids and volumes of solids of revolution is expressed in the following theorem.

If a plane area is revolved about an axis lying in its plane and not crossing it, the volume of the solid of revolution thus generated is equal to the product of the plane area by the circumference described by its centroid.

Proof. Let the area in the figure be revolved about the x -axis. The rectangular element of area within the region S at P will generate a hollow circular cylinder whose volume ΔV is given by

$$\Delta V = \pi(y + \Delta y)^2 \Delta x - \pi y^2 \Delta x.$$

Factoring and simplifying, we get

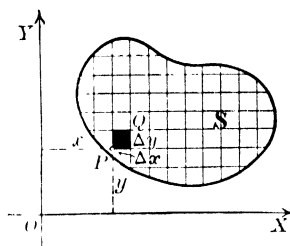
$$\Delta V = 2\pi(y + \frac{1}{2}\Delta y) \Delta x \Delta y.$$

Now, in (1), Art. 245, (x, y) in $f(x, y)$ is a point "either within the rectangle PQ or on its perimeter." But $(x, y + \frac{1}{2}\Delta y)$ is a point on the perimeter of PQ . Therefore let $f(x, y) = 2\pi y$. Then ΔV has the form $f(x, y) \Delta x \Delta y$, and, by (1), Art. 245, and (C),

$$(1) \quad V_x = 2\pi \iint_S y \, \Delta x \, \Delta y = 2\pi M_x.$$

Finally, using (D), we get

$$(2) \quad V_x = 2\pi \bar{y} \cdot A,$$



where A is the area of the region S . The right-hand member is the product of the area by the circumference described by its centroid. Hence the theorem is proved. We write the result

$$(3) \quad V = 2 \pi \bar{y} \cdot A.$$

If two of the quantities V , \bar{y} , A are known, the other can be found by (3).

ILLUSTRATIVE EXAMPLE. Find the centroid of the trapezoid $OMPB$ of the figure by the Theorem of Pappus.

Solution. Area $OMPB = \frac{1}{2}(3 + 5)8 = 32$. Revolving the figure about OX , the solid formed is a frustum of a cone of revolution. Hence, by (12), Art. 1, since $a = 8$, $R = 5$, $r = 3$,

$$V_v = \frac{8}{3} \pi (25 + 9 + 15) = \frac{392}{3} \pi.$$

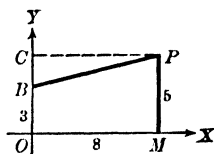
$$\text{Hence, by (3), } \bar{y} = \frac{V_v}{2 \pi A} = \frac{392}{192} = 2.04.$$

Revolving the figure about OY , the volume generated is the difference of the volumes of the cylinder generated by $OC'PM$ and the cone generated by the triangle $BC'P$. Hence

$$V_v = 320 \pi - \frac{128}{3} \pi = \frac{832}{3} \pi.$$

$$\text{Hence, by the theorem, } \bar{x} = \frac{V_v}{2 \pi A} = \frac{832}{192} = 4 \frac{1}{3}.$$

The centroid is $(4 \frac{1}{3}, 2.04)$. *Ans.*



PROBLEMS

Find the centroid of the area bounded by each of the following curves:

1. $y = x^3$, $y = 4x$. (Area in first quadrant.) *Ans.* $(\frac{16}{15}, \frac{64}{15})$.
2. $y = 6x - x^2$, $y = x$. $(\frac{5}{2}, 5)$.
3. $y = 4x - x^2$, $y = 2x - 3$. $(1, \frac{3}{5})$.
4. $x^2 = 4y$, $x - 2y + 4 = 0$. $(1, \frac{8}{5})$.
5. $y = x^2$, $2x - y + 3 = 0$. $(1, \frac{17}{5})$.
6. $y = x^2 - 2x - 3$, $y = 2x - 3$. $(2, -\frac{8}{5})$.
7. $y^2 = x$, $x + y = 2$, $y = 0$. (First quadrant.) $(\frac{32}{5}, \frac{5}{14})$.
8. $y^2 = x$, $x + y = 2$, $x = 0$. $(\frac{8}{5}, \frac{11}{10})$.
9. $y^3 = x^2$, $2y = x$. $(\frac{10}{3}, \frac{4}{3})$.
10. $4y = 3x^2$, $2y^2 = 9x$. $(\frac{9}{10}, \frac{27}{10})$.
11. $y^2 = 2x$, $y = x - x^2$. $(\frac{14}{5}, -\frac{11}{5})$.
12. $y^2 = 8x$, $x + y = 6$. $(\frac{24}{5}, -4)$.
13. $y^2 = 4x$, $y^2 = 5 - x$. $(\frac{11}{5}, 0)$.
14. $y = 6x - x^2$, $x + y = 6$. $(\frac{7}{2}, 5)$.

15. $x = 4y - y^2, y = x.$

Ans. $(\frac{1}{5}, \frac{3}{2}).$

16. $y = 4x - x^2, y = 5 - 2x.$

$(3, \frac{3}{5}).$

17. $y^2 = 4x, 2x - y = 4.$

$(\frac{8}{5}, 1).$

18. $y = x^2 - 2x - 3, y = 6x - x^2 - 8.$

$(2, 1).$

19. $x^2 + y^2 = 1, x + y = 1.$

$(0.585, 0.585).$

20. $x^2 + y^2 = 32, y^2 = 4x.$

21. $y^2 = 4x, 2x + y = 4.$

22. $x^2 + y^2 - 10x = 0, x^2 = y.$

23. $x^2 = y, 2y = 6x - x^2.$

24. $x^3 + y^3 = a^3.$ (Area in first quadrant.)

$(\frac{256a}{315\pi}, \frac{256a}{315\pi}).$

25. $x^{\frac{1}{2}} + y^{\frac{1}{2}} = a^{\frac{1}{2}}, x = 0, y = 0.$

$(\frac{a}{5}, \frac{a}{5}).$

26. Find the centroid of the area under one arch of the cycloid
 $x = a(\theta - \sin \theta), y = a(1 - \cos \theta).$

Ans. $(\pi a, \frac{5a}{6}).$

27. Using the Theorem of Pappus, find the centroid of a semicircle.

Ans. Distance from diameter = $\frac{4r}{3\pi}.$

28. Using the Theorem of Pappus, find the centroid of the area of the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ which lies in the first quadrant.

Ans. $(\frac{4a}{3\pi}, \frac{4b}{3\pi}).$

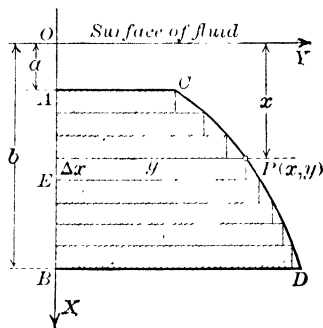
29. Using the Theorem of Pappus find the volume of the torus generated by revolving the circle $(x - b)^2 + y^2 = a^2 (b > a)$ about the y -axis.

Ans. $2\pi^2 a^2 b.$

30. A rectangle is revolved about an axis which lies in its plane and is perpendicular to a diagonal at its extremity. Find the volume of the solid generated.

251. **Center of fluid pressure.** The problem of calculating the pressure of a fluid on a vertical wall was discussed in Art. 179.

The pressures on the rectangular elements of the figure constitute a system of parallel forces, since they are perpendicular to the plane of the area XOY . The resultant of this system of forces is the total fluid pressure P , given by (D), Art. 179.



$$(1) \quad P = \overline{W} \int_a^b yx \, dx.$$

The point of application of P is called the *center of fluid pressure*. We wish to find the x -coordinate ($= x_0$) of this point.

To this end we use the *principle of force moments*. This may be stated thus:

The sum of the turning moments of a system of parallel forces about an axis is equal to the turning moment of their resultant about this axis.

Now the fluid pressure dP on the rectangular element EP is, by Art. 179,

$$(2) \quad dP = \bar{W}xy \, \Delta x.$$

The turning moment of this force about the axis OY is the product of dP by its lever arm OE ($= x$), or, using (2),

$$(3) \quad \text{Turning moment of } dP = x \, dP = \bar{W}x^2y \, \Delta x.$$

Hence we have, for the entire turning moment for the distributed fluid pressure,

$$(4) \quad \text{Total turning moment} = \int_a^b \bar{W}x^2y \, dx.$$

But the turning moment of the resultant fluid pressure P is x_0P . Hence

$$(5) \quad x_0P = \bar{W} \int_a^b x^2y \, dx.$$

Solving for x_0 and using (1), we get the formula for the *depth of the center of pressure*

$$(6) \quad x_0 = \frac{\int_a^b x^2 dA}{\int_a^b x \, dA},$$

where dA = element of area $= y \, dx$.

The denominator in (6) is the moment of area of $ABCD$ with respect to OY (see Art. 177). The numerator is an integral not met with hitherto. It is called the *moment of inertia of the area $ABCD$ about OY* .

The letter I is commonly used for moment of inertia about an axis, and a subscript is attached to designate the axis. Thus (6) becomes

$$(7) \quad x_0 = \frac{I_y}{M_y}.$$

The usual notation for moment of inertia about an axis l is

$$(8) \quad I_l = \int r^2 dA,$$

in which

$$(9) \quad r = \text{distance of the element } dA \text{ from the axis } l.$$

The problem of this article is one of many which lead to moments of inertia. In the following section the calculation of moments of inertia by double and single integration is explained. Applications are also given.

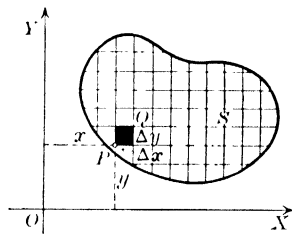
252. Moment of inertia of an area. In mechanics the moment of inertia of an area about an axis is an important concept. The calculation of moments of inertia will now be explained. We follow the rule of Art. 248.

For the elementary rectangle PQ at $P(x, y)$ the moment of inertia about OX is defined as

$$(1) \quad y^2 \Delta x \Delta y,$$

and about the y -axis it is

$$(2) \quad x^2 \Delta x \Delta y.$$



Then, if I_x and I_y are the corresponding moments of inertia for the entire area, we have (compare (8), Art. 251)

$$(E) \quad I_x = \iint y^2 dx dy, \quad I_y = \iint x^2 dx dy.$$

The radii of gyration r_x and r_y are given by

$$(F) \quad r_x^2 = \frac{I_x}{\text{area}}, \quad r_y^2 = \frac{I_y}{\text{area}}.$$

In (E) the functions whose integrals are taken over the area are, respectively, $f(x, y) = y^2$, and $f(x, y) = x^2$.

Formulas (E) become simple for an area "under a curve," that is, an area bounded by a curve, the x -axis and two ordinates. Thus we obtain

$$(3) \quad \begin{aligned} I_x &= \int_a^b \int_0^y y^2 dy dx = \frac{1}{3} \int_a^b y^3 dx, \\ I_y &= \int_a^b \int_0^y x^2 dy dx = \int_a^b x^2 y dx. \end{aligned}$$

In these equations y is the ordinate of a point on the curve, and its value in terms of x must be found from the equation of this curve and substituted in the integrand.

Formulas for moments of inertia I are written in the form

$$(G) \quad I = Ar^2,$$

where A = area and r = radius of gyration. Solving (F) for I_x and I_y will give this form.

Dimensions. If the linear unit is 1 in., the moment of inertia has the dimensions in.⁴. By (F), r_x and r_y are lengths, in inches.

ILLUSTRATIVE EXAMPLE 1. Find I_x , I_y , and the corresponding radii of gyration for the area of Illustrative Example 1, Art. 246.

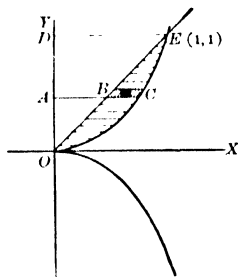
Solution. Using the same order of integration and the same limits as before, we have, by (E),

$$I_x = \int_0^1 \int_y^{y^{\frac{2}{3}}} y^2 dx dy = \int_0^1 (y^{\frac{5}{3}} - y^2) dy = \frac{1}{4}.$$

$$I_y = \int_0^1 \int_y^{y^{\frac{2}{3}}} x^2 dx dy = \frac{1}{3} \int_0^1 (y^2 - y^3) dy = \frac{1}{6}.$$

Since $A = \text{area} = \frac{1}{6}$, we find, by (F),

$$r_x = 0.48, \quad r_y = 0.53. \quad \text{Ans.}$$



ILLUSTRATIVE EXAMPLE 2. Find I_x and I_y for the parabolic segment BOC in the figure.

Solution. With the axes of coordinates as drawn, the equation of the bounding parabola is

$$(4) \quad y^2 = 2px.$$

Since $B(a, b)$ is a point on the curve, we get, by substituting $x = a$, $y = b$ in (4), $b^2 = 2pa$. Solving this equation for $2p$ and substituting its value in (4), we obtain

$$(5) \quad y^2 = \frac{b^2x}{a}, \quad \text{or} \quad y = \frac{bx^{\frac{1}{2}}}{a^{\frac{1}{2}}}.$$

The moments of inertia for the area under the parabola OPB in the first quadrant will be half the required moments. Hence, using (3), and substituting the value of y from (5), we get

$$\frac{1}{2} I_x = \frac{1}{3} \int_0^a \frac{b^3}{a^{\frac{3}{2}}} x^{\frac{3}{2}} dx = \frac{2}{15} ab^3. \quad \therefore I_x = \frac{4}{15} ab^3.$$

$$\frac{1}{2} I_y = \int_0^a x^2 \frac{b}{a^{\frac{1}{2}}} x^{\frac{1}{2}} dx = \frac{2}{7} a^3 b. \quad \therefore I_y = \frac{4}{7} a^3 b.$$

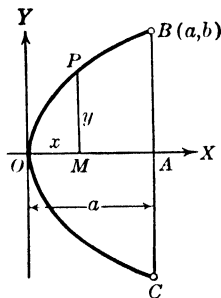
For the area of the segment, we find

$$\frac{1}{2} A = \int_0^a y dx = \int_0^a \frac{b}{a^{\frac{1}{2}}} x^{\frac{1}{2}} dx = \frac{2}{3} ab. \quad \therefore A = \frac{4}{3} ab.$$

Hence, by (F), $r_x^2 = \frac{I_x}{A} = \frac{1}{5} b^2$, and $I_x = \frac{1}{5} Ab^2$,

$$r_y^2 = \frac{I_y}{A} = \frac{3}{7} a^2, \quad \text{and} \quad I_y = \frac{3}{7} Aa^2.$$

The results are in the form (G). *Ans.*



In the figure on page 325 the axis OY lies in the surface of the fluid. If we denote this axis in any figure by s , then the depth of the center of pressure, is by (7), Art. 251

$$(6) \quad x_0 = \frac{I_s}{M_s} = \frac{r_s^2}{h_s},$$

if r_s = radius of gyration about the axis s ,
and h_s = depth of centroid below the axis s .

ILLUSTRATIVE EXAMPLE 3. Find the depth of the center of pressure on the trapezoidal water gate of the figure. Compare Illustrative Example 2, Art. 179.

Solution. Choose axes OX and OY as shown, and draw an elementary horizontal strip. Let the distance of this strip from the axis s at the water level be r . Then

$$r = 8 - y, \quad dA = 2x \, dy.$$

Hence, by (8), Art. 251, and by the definition of moment of area (Art. 177), we have

$$(7) \quad I_s = \int r^2 dA = \int (8 - y)^2 2x \, dy,$$

$$(8) \quad M_s = \int r dA = \int (8 - y) 2x \, dy.$$

The equation of AB is $y = 2x - 8$.

Solving this for x , substituting in (7) and (8), and integrating with limits $y = 0$, $y = 4$, we obtain

$$I_s = \int_0^4 (8 - y)^2 (8 + y) dy = 1429 \frac{1}{3},$$

$$M_s = \int_0^4 (64 - y^2) dy = 234 \frac{2}{3}.$$

Hence, by (7), Art. 251, $x_0 = 6.09$. *Ans.*

253. Polar moment of inertia. The moment of inertia of the elementary rectangle PQ about the origin O is the product of the area and \overline{OP}^2 , that is,

$$(1) \quad (x^2 + y^2) \Delta x \, \Delta y.$$

Hence, by Art. 248, for the entire area

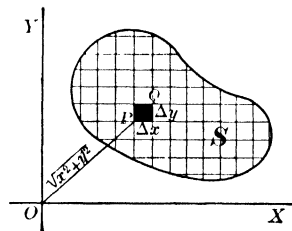
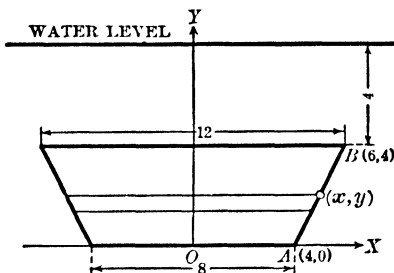
$$(2) \quad I_0 = \iint (x^2 + y^2) dx \, dy.$$

We may, however, write the right-hand member as the sum of two integrals, for (2) is clearly the same as

$$(3) \quad I_0 = \iint x^2 dx \, dy + \iint y^2 dx \, dy = I_x + I_y.$$

Hence we have the following theorem.

The moment of inertia of an area about the origin equals the sum of its moments of inertia about the x -axis and the y -axis.



PROBLEMS

Find I_x , I_y , and I_0 for each of the areas described below.

1. The semicircle which is to the right of the y -axis and which is bounded by $x^2 + y^2 = r^2$.

$$\text{Ans. } I_x = I_y = \frac{Ar^2}{4}.$$

2. The isosceles triangle of height h and base a whose vertices are $(0, 0)$, $(h, \frac{a}{2})$, $(h, -\frac{a}{2})$.

$$\text{Ans. } I_x = \frac{Aa^2}{24}, I_y = \frac{Ah^2}{2}.$$

3. The right triangle whose vertices are $(0, 0)$, (b, a) , $(b, 0)$.

$$\text{Ans. } I_x = \frac{Aa^2}{6}, I_y = \frac{Ab^2}{2}.$$

4. The ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$.

$$\text{Ans. } I_x = \frac{Ab^2}{4}, I_y = \frac{Aa^2}{4}.$$

5. The area in the first quadrant bounded by $y^2 = 4x$, $x = 4$, $y = 0$.

$$\text{Ans. } I_x = \frac{16A}{5}, I_y = \frac{48A}{7}.$$

6. The area included between the ellipse $\frac{x^2}{9} + \frac{y^2}{4} = 1$ and the circle $x^2 + y^2 = 2y$.

$$\text{Ans. } I_x = \frac{19A}{20}, I_y = \frac{53A}{20}.$$

7. The area included between the ellipses $\frac{x^2}{16} + \frac{y^2}{9} = 1$ and $x^2 + \frac{y^2}{4} = 1$.

$$\text{Ans. } I_x = \frac{5A}{2}, I_y = \frac{19A}{4}.$$

8. The area included between the circle $x^2 + y^2 = 16$ and the circle $x^2 + (y + 2)^2 = 1$.

$$\text{Ans. } I_x = \frac{239A}{60}, I_y = \frac{17A}{4}.$$

9. The area included between the circle $x^2 + y^2 = 36$ and the circle $x^2 + (y + 3)^2 = 4$.

$$\text{Ans. } I_x = \frac{71A}{8}, I_y = 10A.$$

10. The area between the circle $x^2 + y^2 = 4$ and the ellipse $\frac{x^2}{36} + \frac{y^2}{16} = 1$.

$$\text{Ans. } I_x = \frac{23A}{5}, I_y = \frac{53A}{5}.$$

11. The entire area bounded by $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$. $\text{Ans. } I_x = I_y = \frac{7A}{64}.$

12. Find the depth of the center of pressure on a triangular water gate having its vertex below the base, which is horizontal and on a level with the surface of the water.

13. Find the depth of the center of pressure on a rectangular water gate 8 ft. wide and 4 ft. deep when the level of the water is 5 ft. above the top of the gate. $\text{Ans. } 7.19 \text{ ft. below the surface of the water.}$

14. Find the depth of the center of pressure on the end of a horizontal cylindrical oil tank of diameter 5 ft. when the depth of oil is (a) 2.5 ft.; (b) 4 ft.; (c) 6 ft.

Ans. (a) $\frac{15}{32}\pi = 1.47$ ft.; (b) approximately 2.4 ft.;
(c) $\frac{221}{56} = 3.95$ ft.

254. **Polar coördinates. Plane area.** When the equations of the curves bounding an area are given in polar coördinates, certain modifications are necessary.

The area is now divided into elementary portions, as follows:

Draw arcs of circles with the common center O with successive radii differing by $\Delta\rho$. Thus, in Fig. 1, $OP = \rho$, $OS = \rho + \Delta\rho$. Then

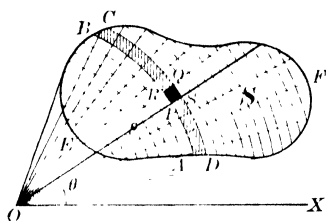


FIG. 1

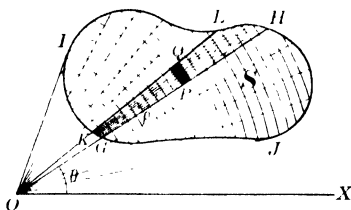


FIG. 2

draw radial lines from O such that the angle between any two consecutive lines is the same and equal to $\Delta\theta$. Thus, in Fig. 1, angle $POR = \Delta\theta$.

The area will now contain a large number of rectangular portions, such as $PSQR$ in Fig. 1.

Let $PSQR = \Delta A$. Now ΔA is the difference of the areas of the circular sectors POR and SOQ . Hence

$$(1) \quad \Delta A = \frac{1}{2}(\rho + \Delta\rho)^2 \Delta\theta - \frac{1}{2}\rho^2 \Delta\theta = \rho \Delta\rho \Delta\theta + \frac{1}{2} \Delta\rho^2 \Delta\theta.$$

The function $f(x, y)$ of Art. 245 is to be replaced by a function using polar coördinates. Let this be $F(\rho, \theta)$. Then, proceeding as in Art. 245, we choose a point (ρ, θ) of ΔA , form the product

$$F(\rho, \theta) \Delta A$$

for each ΔA within the region S , add these products, and finally let $\Delta\rho \rightarrow 0$ and $\Delta\theta \rightarrow 0$. It is shown in Art. 258 that the limiting value of this double sum may be found by successive integration. We now write (compare (1), Art. 245)

$$(2) \quad \lim_{\substack{\Delta\rho \rightarrow 0 \\ \Delta\theta \rightarrow 0}} \sum \sum F(\rho, \theta) \Delta A = \iint_S F(\rho, \theta) \rho \, d\rho \, d\theta,$$

and call it the double integral of the function $F(\rho, \theta)$ taken over the region S .

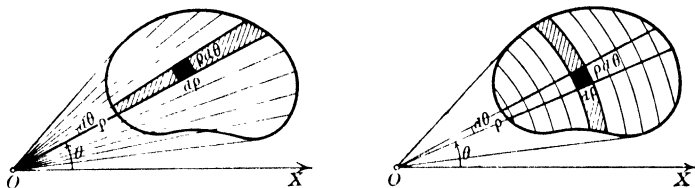
Note in (2) that the value of ΔA in (1) has been replaced in the integral by $\rho d\rho d\theta$.

The simplest case of (2) is that of finding the area of the region S . We then have

$$(H) \quad A = \iint \rho d\rho d\theta = \iint \rho d\theta d\rho.$$

These are easily remembered if we think of the elements (checks) as being rectangles with dimensions $\rho d\theta$ and $d\rho$, and hence of area $\rho d\theta d\rho$.

The figures below illustrate, in a general way, the difference in the processes indicated by the two integrals.



In the first, we integrate first with respect to ρ , since $d\rho$ precedes $d\theta$, keeping θ constant. This process will cover the radial strip $KGH L$ in Fig. 2, p. 512. The limits for ρ are $\rho = OG$ and $\rho = OH$, found by solving the equation (or equations) of the bounding curve (or curves) for ρ in terms of θ . Then integrate varying θ , the limits being $\theta = \angle JOX$ and $\theta = \angle IOX$.

The second integral in (2) is worked out by integrating with respect to θ , ρ remaining constant. This step covers the circular strip $ABCD$ in Fig. 1, p. 512, between two consecutive circular arcs. Then integrate varying ρ .

When the area is bounded by a curve and two of its radii vectores (area swept over by the radius vector), we obtain from the first form in (H)

$$A = \int_{\alpha}^{\beta} \int_0^{\rho} \rho d\rho d\theta = \frac{1}{2} \int_{\alpha}^{\beta} \rho^2 d\theta,$$

which agrees with (D), Art. 159.

Double integrals in polar coördinates have one of the forms

$$(3) \quad \iint F(\rho, \theta) \rho d\rho d\theta \quad \text{or} \quad \iint F(\rho, \theta) \rho d\theta d\rho.$$

ILLUSTRATIVE EXAMPLE 1. Find the limits for the double integral giving some required property related to the area inside the circle $\rho = 2r \cos \theta$ and outside the circle $\rho = r$.

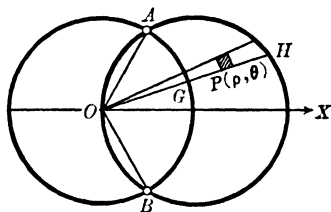
Solution. The points of intersection are $A(r, \frac{\pi}{3})$, and $B(r, -\frac{\pi}{3})$. Use the first form in (3).

The limits for ρ are

$$\rho = OG = r,$$

$$\rho = OH = 2r \cos \theta;$$

for θ they are $\frac{\pi}{3}$ and $-\frac{\pi}{3}$. *Ans.*



ILLUSTRATIVE EXAMPLE 2. Find the area inside the circle $\rho = 2r \cos \theta$ and outside the circle $\rho = r$.

Solution. From Illustrative Example 1 above, we have

$$A = \int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} \int_r^{2r \cos \theta} \rho \, d\rho \, d\theta = \int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} \frac{1}{2} (4r^2 \cos^2 \theta - r^2) d\theta = r^2 (\frac{1}{3} \pi + \frac{1}{2} \sqrt{3}) = 1.91 r^2. \text{ Ans.}$$

255. Problems using polar coördinates. There should now be no difficulty in establishing the following formulas:

$$(1) \quad M_x = \iint \rho^2 \sin \theta \, d\rho \, d\theta.$$

$$(2) \quad M_y = \iint \rho^2 \cos \theta \, d\rho \, d\theta.$$

$$(3) \quad I_x = \iint \rho^3 \sin^2 \theta \, d\rho \, d\theta.$$

$$(4) \quad I_y = \iint \rho^3 \cos^2 \theta \, d\rho \, d\theta.$$

$$(5) \quad I_0 = \iint \rho^3 \, d\rho \, d\theta.$$

The order of the differentials will have to be changed if integration with respect to θ is performed first.

ILLUSTRATIVE EXAMPLE 1. On account of important applications the moments of inertia of a circle are now worked out.

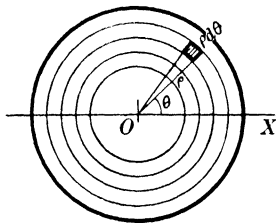
Let a = radius. Then, by (5), the polar moment of inertia with respect to the center is

$$(6) \quad I_0 = \int_0^a \left[\int_0^{2\pi} d\theta \right] \rho^3 \, d\rho = \frac{\pi a^4}{2} = \frac{A}{2} a^2,$$

where A = area of the circle.

Also, since $I_x = I_y$, by symmetry, we have, by (3),
Art. 253,

$$(7) \quad I_x = \frac{1}{2} I_0 = \frac{A}{4} a^2.$$



In words: *The polar moment of inertia of a circle with respect to its center equals the product of half the area and the square of the radius; the polar moment of inertia with respect to any diameter equals the product of one fourth the area and the square of the radius.*

ILLUSTRATIVE EXAMPLE 2. Find the centroid of a loop of the lemniscate

$$\rho^2 = a^2 \cos 2\theta.$$

Solution. Since OX is an axis of symmetry, we have $\bar{y} = 0$.

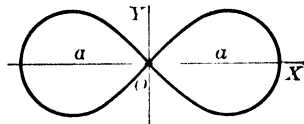
$$\begin{aligned} \frac{1}{2} A &= \int_0^{\frac{1}{2}\pi} \int_0^{a\sqrt{\cos 2\theta}} \rho \, d\rho \, d\theta \\ &= \frac{a^2}{2} \int_0^{\frac{1}{2}\pi} \cos 2\theta \, d\theta = \frac{a^2}{4}. \end{aligned}$$

$$\frac{1}{2} M_y = \int_0^{\frac{1}{2}\pi} \int_0^{a\sqrt{\cos 2\theta}} \rho^2 \cos \theta \, d\rho \, d\theta = \frac{1}{3} a^3 \int_0^{\frac{1}{2}\pi} (\cos 2\theta)^{\frac{3}{2}} \cos \theta \, d\theta.$$

$$= \frac{1}{3} a^3 \int_0^{\frac{1}{2}\pi} (1 - 2 \sin^2 \theta)^{\frac{3}{2}} \cos \theta \, d\theta \quad \text{by (5), Art. 2}$$

$$= \frac{\sqrt{2}}{6} a^3 \int_0^1 (1 - z^2)^{\frac{3}{2}} dz \left(\text{if } \sin \theta = \frac{1}{2} z\sqrt{2} \right) = \frac{\pi}{32} a^3 \sqrt{2}.$$

Hence $\bar{x} = \frac{M_y}{A} = \frac{\pi}{8} a \sqrt{2} = 0.55 a$. Ans.

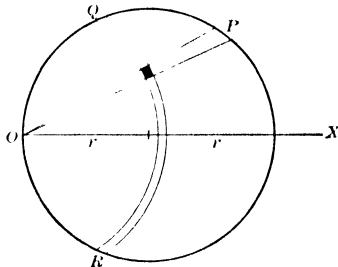


ILLUSTRATIVE EXAMPLE 3. Find I_0 over the region bounded by the circle $\rho = 2r \cos \theta$.

Solution. Summing up for the elements in the triangular-shaped strip OP , the ρ -limits are zero and $2r \cos \theta$ (found from the equation of the circle).

Summing up for all such strips, the θ -limits are $-\frac{\pi}{2}$ and $\frac{\pi}{2}$. Hence, by (5),

$$I_0 = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{2r \cos \theta} \rho^3 \, d\rho \, d\theta = \frac{3}{2} \frac{\pi r^4}{2}. \quad \text{Ans.}$$



Or, summing up first for the elements in a circular strip (as QR), we have

$$I_0 = \int_0^{2r} \int_{-\arccos \frac{\rho}{2r}}^{\arccos \frac{\rho}{2r}} \rho^3 \, d\theta \, d\rho = \frac{3}{2} \frac{\pi r^4}{2}. \quad \text{Ans.}$$

PROBLEMS

1. Find the area inside the circle $\rho = \frac{3}{2}$ and to the right of the line $4\rho \cos \theta = 3$.

Ans. $\frac{3(4\pi - 3\sqrt{3})}{16}$.

2. Find the area which is inside the circle $\rho = 3 \cos \theta$ and outside the circle $\rho = \frac{3}{2}$.

Ans. $\frac{3(2\pi + 3\sqrt{3})}{8}$.

3. Find the area which is inside the circle $\rho = 3 \cos \theta$ and outside the circle $\rho = \cos \theta$. *Ans.* 2π .

4. Find the area inside the cardioid $\rho = 1 + \cos \theta$ and to the right of the line $4 \rho \cos \theta = 3$. *Ans.* $\frac{\pi}{2} + \frac{9\sqrt{3}}{16}$.

5. Find the area which is inside the cardioid $\rho = 1 + \cos \theta$ and outside the circle $\rho = 1$. *Ans.* $\frac{\pi}{4} + 2$.

6. Find the area which is inside the circle $\rho = 1$ and outside the cardioid $\rho = 1 + \cos \theta$. *Ans.* $2 - \frac{\pi}{4}$.

7. Find the area which is inside the circle $\rho = 3 \cos \theta$ and outside the cardioid $\rho = 1 + \cos \theta$. *Ans.* π .

8. Find the area which is inside the circle $\rho = 1$ and outside the parabola $\rho(1 + \cos \theta) = 1$. *Ans.* $\frac{\pi}{2} - \frac{2}{3}$.

9. Find the area which is inside the cardioid $\rho = 1 + \cos \theta$ and outside the parabola $\rho(1 + \cos \theta) = 1$. *Ans.* $\frac{3\pi}{4} + \frac{4}{3}$.

10. Find the area which is inside the circle $\rho = \cos \theta + \sin \theta$ and outside the circle $\rho = 1$. *Ans.* $\frac{1}{2}$.

11. Find the area which is inside the circle $\rho = \sin \theta$ and outside the cardioid $\rho = 1 - \cos \theta$. *Ans.* $1 - \frac{\pi}{4}$.

12. Find the area which is inside the lemniscate $\rho^2 = 2a^2 \cos 2\theta$ and outside the circle $\rho = a$. *Ans.* $0.684a^2$.

13. Find the area which is inside the cardioid $\rho = 4(1 + \cos \theta)$ and outside the parabola $\rho(1 - \cos \theta) = 3$. *Ans.* 5.504 .

14. Find the area which is inside the circle $\rho = 2a \cos \theta$ and outside the circle $\rho = a$. Find the centroid of the area and I_x and I_y .

$$\begin{aligned} \text{Ans. } A &= \left(\frac{\pi}{3} + \frac{\sqrt{3}}{2} \right) a^2, \quad \bar{x} = \frac{(8\pi + 3\sqrt{3})a}{2(2\pi + 3\sqrt{3})}, \\ I_x &= \left(\frac{\pi}{12} + \frac{3\sqrt{3}}{16} \right) a^4, \quad I_y = \left(\frac{3\pi}{4} + \frac{11\sqrt{3}}{16} \right) a^4. \end{aligned}$$

15. Find the centroid of the area bounded by the cardioid $\rho = a(1 + \cos \theta)$. *Ans.* $\bar{x} = \frac{5a}{6}$.

16. Find the centroid of the area bounded by a loop of the curve $\rho = a \cos 2\theta$. *Ans.* $\bar{x} = \frac{128\sqrt{2}a}{105\pi}$.

17. Find the centroid of the area bounded by a loop of the curve $\rho = a \cos 3\theta$. *Ans.* $\bar{x} = \frac{81\sqrt{3}a}{80\pi}$.

18. Find I_v for the lemniscate $\rho^2 = a^2 \cos 2\theta$. *Ans.* $\frac{A}{48} (3\pi + 8)a^2$.
19. Find I_r for the cardioid $\rho = a(1 + \cos \theta)$.
20. Find I_r and I_v for one loop of the curve $\rho = a \cos 2\theta$.
21. Prove from (1), Art. 254, that

$$\lim_{\substack{\Delta\rho \rightarrow 0 \\ \Delta\theta \rightarrow 0}} \frac{\Delta A}{\rho \Delta\rho \Delta\theta} = 1,$$

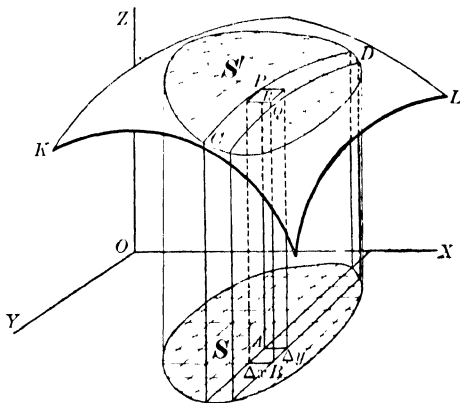
and therefore ΔA "differs from $\rho \Delta\rho \Delta\theta$ by an infinitesimal of higher order" (Art. 99). Then ΔA in the left-hand member of (2), Art. 254, may be replaced by $\rho \Delta\rho \Delta\theta$. (Proof omitted.)

256. General method for finding the areas of curved surfaces. The method given in Art. 164 applied only to the area of a surface of revolution. We shall now give a more general method. Let

$$(1) \quad z = f(x, y)$$

be the equation of the surface KL in the figure, and suppose it is required to calculate the area of the region S' lying on the surface.

Denote by S the region on the XOY -plane which is the orthogonal projection of S' on that plane. Now pass planes parallel to YOZ and XOZ at common distances Δx and Δy respectively. As in Art. 244, these planes form truncated prisms (as PB) bounded at the top by a portion (as PQ) of the given surface whose projection on the XOY -plane is a rectangle of area $\Delta x \Delta y$ (as AB). This rectangle also forms the lower base of the prism. The coördinates of P are (x, y, z) .



Now consider the plane tangent to the surface KL

at P . Evidently the same rectangle AB is the projection on the XOY -plane of that portion of the tangent plane (PR) which is intercepted by the prism PB . Assuming γ as the angle the tangent plane makes with the XOY -plane, we have

$$\text{Area } AB = \text{area } PR \cdot \cos \gamma,$$

[The projection of a plane area upon a second plane is equal to the area of the portion projected multiplied by the cosine of the angle between the planes.]

or

$$\Delta y \Delta x = \text{area } PR \cdot \cos \gamma.$$

Now γ is equal to the angle between OZ and a line from O perpendicular to the tangent plane. Hence from (H), Art. 237, and (2) and (3), Art. 4, we have

$$\cos \gamma = \frac{1}{\left[1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2\right]^{\frac{1}{2}}}.$$

Then
$$\text{Area } PR = \left[1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2\right]^{\frac{1}{2}} \Delta y \Delta x.$$

This we take as the element of area of the region S' . We then define the area of the region S' as

$$\lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0}} \sum \sum \left[1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2\right]^{\frac{1}{2}} \Delta y \Delta x,$$

the summation extending over the region S , as in Art. 245. Denoting by A the area of the region S' , we have

$$(I) \quad A = \iint_S \left[1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2\right]^{\frac{1}{2}} dy dx,$$

the limits of integration depending on the projection on the XOY -plane of the region whose area we wish to calculate. Thus, for (I) we choose our limits from the boundary curve or curves of the region S in the XOY -plane precisely as we have been doing in the previous sections.

Before integrating, the expression

$$1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2$$

must be reduced to a function of x and y only, by using the equation of the curved surface on which the area lies.

If it is more convenient to project the required area on the XOZ -plane, use the formula

$$(J) \quad A = \iint_S \left[1 + \left(\frac{\partial y}{\partial x}\right)^2 + \left(\frac{\partial y}{\partial z}\right)^2\right]^{\frac{1}{2}} dz dx,$$

where the limits are found from the boundary of the region S , which is now the projection of the required area on the XOZ -plane.

Similarly, we may use

$$(K) \quad A = \iint_S \left[1 + \left(\frac{\partial x}{\partial y}\right)^2 + \left(\frac{\partial x}{\partial z}\right)^2\right]^{\frac{1}{2}} dz dy,$$

the limits being found from the projection of the required area on the YOZ -plane.

In some problems it is required to find the area of a portion of one surface intercepted by a second surface. In such cases the partial derivatives required for substitution in the formula should be found from the equation of the surface whose partial area is wanted.

Since the limits are found by projecting the required area on one of the coördinate planes, it should be remembered that

To find the projection of the area required on the XOY-plane, eliminate z between the equations of the surfaces whose intersections form the boundary of the area.

Similarly, we eliminate y to find the projection on the XOZ-plane, and x to find it on the YOZ-plane.

This area of a curved surface gives a further illustration of *integration of a function over a given area*. Thus in (I) we integrate the function

$$\left[1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{\frac{1}{2}}$$

over the projection of the required curved surface on the XOY-plane.

As remarked above, (J) and (K) must be reduced to

$$\iint f(x, z) dz dx \quad \text{and} \quad \iint f(y, z) dy dz,$$

respectively, by means of the equation of the surface on which the required curved surface lies.

ILLUSTRATIVE EXAMPLE 1. Find the area of the surface of the sphere

$$x^2 + y^2 + z^2 = r^2$$

by double integration.

Solution. Let ABC in the figure be one eighth of the surface of the sphere. Here

$$\frac{\partial z}{\partial x} = -\frac{x}{z}, \quad \frac{\partial z}{\partial y} = -\frac{y}{z},$$

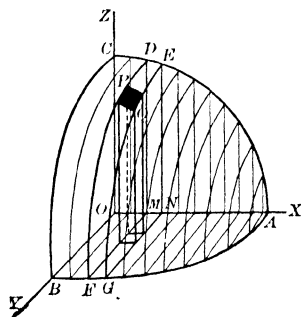
$$\text{and} \quad 1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 = 1 + \frac{x^2}{z^2} + \frac{y^2}{z^2} = \frac{x^2 + y^2 + z^2}{z^2} = \frac{r^2}{r^2 - x^2 - y^2}.$$

The projection of the area required on the XOY-plane is AOB , a region bounded by $x = 0 (=OB)$; $y = 0 (=OA)$; $x^2 + y^2 = r^2 (=BA)$.

Integrating first with respect to y , we sum up all the elements along a strip (as $DEGF$) which is also projected on the XOY-plane in a strip (as $MNGF$); that is, our y -limits are zero and $MF (= \sqrt{r^2 - x^2})$. Then integrating with respect to x sums up all such strips composing the surface ABC ; that is, our x -limits are zero and $OA (=r)$. Substituting in (I), we get

$$\frac{A}{8} = \int_0^r \int_0^{\sqrt{r^2-x^2}} \frac{r dy dx}{\sqrt{r^2-x^2-y^2}} = \frac{\pi r^2}{2},$$

or $A = 4 \pi r^2$. Ans.



ILLUSTRATIVE EXAMPLE 2. The center of a sphere of radius r is on the surface of a right cylinder, the radius of whose base is $\frac{r}{2}$. Find the area of the surface of the cylinder intercepted by the sphere.

Solution. Taking the origin at the center of the sphere, an element of the cylinder for the z -axis, and a diameter of a right section of the cylinder for the x -axis, the equation of the sphere is

$$x^2 + y^2 + z^2 = r^2,$$

and of the cylinder $x^2 + y^2 = rx$.

$ODAPB$ is evidently one fourth of the cylindrical surface required. Since this area projects into the semicircular arc ODA on the XOY -plane, there is no region S from which to determine our limits in this plane; hence we shall project our area on, say, the XOZ -plane. Then the region S over which we integrate is $OACB$, which is bounded by $z = 0$ ($= OA$), $x = 0$ ($= OB$), and $z^2 + rx = r^2$ ($= ACB$), the last equation being found by eliminating y between the equations of the two surfaces.

Integrating first with respect to z means that we sum up all the elements in a vertical strip (as PD), the z -limits being zero and $\sqrt{r^2 - rx}$. Then, on integrating with respect to x , we sum up all such strips, the x -limits being zero and r .

Since the required surface lies on the cylinder, the partial derivatives required for formula (J) must be found from the equation of the cylinder.

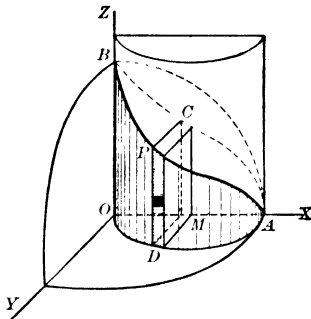
$$\text{Hence} \quad \frac{\partial y}{\partial x} = \frac{r - 2x}{2y}, \quad \frac{\partial y}{\partial z} = 0.$$

Substituting in (J),

$$\frac{A}{4} = \int_0^r \int_0^{\sqrt{r^2 - rx}} \left[1 + \left(\frac{r - 2x}{2y} \right)^2 \right]^{\frac{1}{2}} dz dx.$$

Substituting the value of y in terms of x from the equation of the cylinder,

$$A = 2r \int_0^r \int_0^{\sqrt{r^2 - rx}} \frac{dz dx}{\sqrt{rx - x^2}} = 2r \int_0^r \frac{\sqrt{r^2 - rx}}{\sqrt{rx - x^2}} dx = 2r \int_0^r \sqrt{\frac{r}{x}} dx = 4r^2.$$



PROBLEMS

1. In the preceding example find the surface of the sphere intercepted by the cylinder.

$$\text{Ans. } 4r \int_0^r \int_0^{\sqrt{r^2 - x^2}} \frac{dy dx}{\sqrt{r^2 - x^2 - y^2}} = 2(\pi - 2)r^2.$$

2. The axes of two equal right circular cylinders, r being the radius of their bases, intersect at right angles. Find the surface of one intercepted by the other.

HINT. Take $x^2 + z^2 = r^2$ and $x^2 + y^2 = r^2$ as the equations of the cylinders.

$$\text{Ans. } 8r \int_0^r \int_0^{\sqrt{r^2 - x^2}} \frac{dy dx}{\sqrt{r^2 - x^2}} = 8r^2.$$

3. Find the area of that portion of the sphere $x^2 + y^2 + z^2 = 2ay$ cut out by one nappe of the cone $x^2 + z^2 = y^2$. *Ans.* $2\pi a^2$.

4. Find the surface of the cylinder $x^2 + y^2 = r^2$ included between the plane $z = mx$ and the XOY -plane. *Ans.* $4r^2m$.

5. Find the area of that part of the plane $\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1$ which is intercepted by the coördinate planes. *Ans.* $\frac{1}{2}\sqrt{b^2c^2 + c^2a^2 + a^2b^2}$.

6. Find the area of the portion of the sphere $x^2 + y^2 + z^2 = 2ay$ which lies within the paraboloid $by = x^2 + z^2$. *Ans.* $2\pi ab$.

7. In the preceding example find the area of the portion of the paraboloid which lies within the sphere.

8. Find the area of the surface of the paraboloid $y^2 + z^2 = 4ax$ intercepted by the parabolic cylinder $y^2 = ax$ and the plane $x = 3a$. *Ans.* $\frac{56}{9}\pi a^2$.

9. In the preceding problem find the area of the surface of the cylinder intercepted by the paraboloid and plane. *Ans.* $(13\sqrt{13} - 1)\frac{a^2}{\sqrt{3}}$.

10. Find the surface of the cylinder $z^2 + (x \cos \alpha + y \sin \alpha)^2 = r^2$ which is situated in the positive compartment of coördinates.

HINT. The axis of this cylinder is the line $z = 0, x \cos \alpha + y \sin \alpha = 0$; and the radius of the base is r . *Ans.* $\frac{r^2}{\sin \alpha \cos \alpha}$.

11. Find the area of that portion of the surface of the cylinder $y^{\frac{2}{3}} + z^{\frac{2}{3}} = a^{\frac{2}{3}}$ bounded by a curve whose projection on the XY -plane is $x^{\frac{2}{3}} + y^{\frac{2}{3}} = a^{\frac{2}{3}}$. *Ans.* $\frac{16}{5}a^2$.

12. Find by integration the area of that portion of the surface of the sphere $x^2 + y^2 + z^2 = 100$ which lies between the parallel planes $x = -8$ and $x = 6$.

257. Volumes found by triple integration. In many cases the volume of a solid bounded by surfaces whose equations are given may be calculated by means of three successive integrations, the process being merely an extension of the methods employed in the preceding articles of this chapter (see also Art. 247).

Suppose the solid in question is divided by planes parallel to the coördinate planes into rectangular parallelepipeds having the dimensions $\Delta z, \Delta y, \Delta x$. The volume of one of these parallelepipeds is

$$\Delta z \cdot \Delta y \cdot \Delta x,$$

and we choose it as the element of volume.

Now sum up all such elements within the region R bounded by the given surfaces by first summing up all the elements in a column parallel to one of the coördinate axes, then summing up all such

columns in a slice parallel to one of the coördinate planes containing that axis, and finally summing up all such slices within the region in question. The volume V of the solid will then be the limit of this triple sum as Δz , Δy , Δx each approach zero as a limit. That is,

$$(1) \quad V = \lim_{\substack{\Delta x \rightarrow 0 \\ \Delta y \rightarrow 0 \\ \Delta z \rightarrow 0}} \sum \sum \sum_R \Delta z \Delta y \Delta x,$$

the summations being extended over the entire region R bounded by the given surfaces. This limit is denoted by

$$(L) \quad V = \iiint_R dz dy dx.$$

By extension of the principle of Art. 245, we speak of (L) as the *triple integral of the function* $f(x, y, z) = 1$ *throughout the region* R . Many problems require the integration of a *variable* function of x , y , and z throughout a given region. The notation is

$$(2) \quad \iiint_R f(x, y, z) dz dy dx,$$

which is, of course, the limit of a triple sum analogous to the double sums we have already discussed. In more advanced treatises it is shown that the triple integral (2) is evaluated by successive integration. The limits are found in the same manner as for (L).

Simple examples of (2) are afforded by the formulas for the centroid $(\bar{x}, \bar{y}, \bar{z})$ (center of gravity) of a homogeneous solid, namely,

$$V\bar{x} = \iiint x dx dy dz, \quad V\bar{y} = \iiint y dx dy dz, \quad V\bar{z} = \iiint z dx dy dz.$$

They are obtained by reasoning as in Art. 249, using moments of volume. In the integrands, (x, y, z) is an interior point. The centroid will lie in any plane of symmetry.

ILLUSTRATIVE EXAMPLE 1. Find the volume of that portion of the ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

which lies in the first octant.

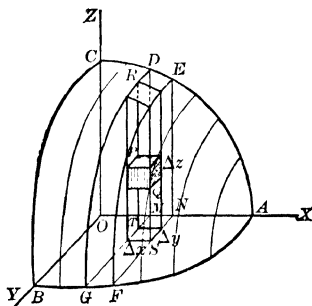
Solution. Let $O-ABC$ be that portion of the ellipsoid whose volume is required, the equations of the bounding surfaces being

$$(3) \quad \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad (= ABC),$$

$$(4) \quad z = 0 \quad (= OAB),$$

$$(5) \quad y = 0 \quad (= OAC),$$

$$(6) \quad x = 0 \quad (= OBC).$$



PQ is an element, being one of the rectangular parallelepipeds with dimensions Δz , Δy , Δx into which the planes parallel to the coordinate planes have divided the region.

Integrating first with respect to z , we sum up all such elements in a column (as RS), the z -limits being zero (from (4)) and $TR = c\sqrt{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}}$ (from (3) by solving for z).

Integrating next with respect to y , we sum up all such columns in a slice (as $DEMN(GF)$), the y -limits being zero (from (5)) and $MG = b\sqrt{1 - \frac{x^2}{a^2}}$ (from the equation of the curve AGB , namely $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$, by solving for y).

Lastly, integrating with respect to x , we sum up all such slices within the entire region $O-ABC$, the x -limits being zero (from (6)) and $OA = a$.

$$\begin{aligned} \text{Hence} \quad V &= \int_0^a \int_0^b \sqrt{1 - \frac{x^2}{a^2}} \int_0^{c\sqrt{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}}} dz \, dy \, dx \\ &= \frac{\pi cb}{4a^2} \int_0^a (a^2 - x^2) dx = \frac{\pi abc}{6}. \end{aligned}$$

Therefore the volume of the entire ellipsoid is $\frac{4\pi abc}{3}$.

ILLUSTRATIVE EXAMPLE 2. Find the volume of the solid bounded by the surfaces

$$(7) \quad z = 4 - x^2 - \frac{1}{4}y^2,$$

$$(8) \quad z = 3x^2 + \frac{1}{4}y^2.$$

Solution. The surfaces are the elliptic paraboloids of the figure. Eliminating z between (7) and (8), we find

$$(9) \quad 4x^2 + \frac{1}{2}y^2 = 4,$$

which is the equation of the cylinder $ABCD$ (see figure) that passes through the curve of intersection of (7) and (8) and has its elements parallel to OZ .

We have

$$(10) \quad V = 4 \int_0^1 \int_0^{2\sqrt{2(1-x^2)}} \int_{3x^2 + \frac{1}{4}y^2}^{4 - x^2 - \frac{1}{4}y^2} dz \, dy \, dx.$$

The limits are found as follows:

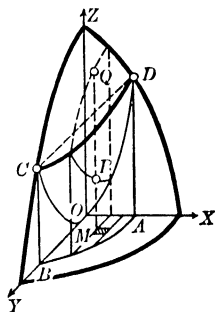
Integrating with respect to z , we sum up the elements of volume $dz \, dy \, dx$ in a column of base $dy \, dx$ from the surface (8) to the surface (7) (MP to MQ in figure). The limits for z are, then, given by the right-hand members in these equations.

Thus we find

$$(11) \quad V = 4 \int_0^1 \int_0^{2\sqrt{2(1-x^2)}} (4 - 4x^2 - \frac{1}{2}y^2) dy \, dx.$$

The limits on this double integral are those for the region OAB , the portion of the area of the base of the cylinder (9) which lies in the first quadrant. Working out (11), we find $V = 4\pi\sqrt{2} = 17.77$ cubic units. *Ans.*

The problem given may be such that the first integration should be performed with respect to x or y , and not with respect to z , as above. The limits must then be determined in accordance with the preceding discussion.



258. Volumes, using cylindrical coördinates. In many problems involving integration the work is much simplified by employing cylindrical coördinates (ρ, θ, z) as defined in (7), p. 6. The cylindrical equation of any one of the bounding surfaces may often be written down directly from its definition. In any case it may be found from its rectangular equation by the substitution

$$(1) \quad x = \rho \cos \theta, \quad y = \rho \sin \theta.$$

Cylindrical coördinates are especially useful when a bounding surface is a surface of revolution. For the equation of such a surface, when the axis is OZ , will have the form $z = f(\rho)$; that is, the coördinate θ will be absent.

Volume under a surface. Let

$$(2) \quad z = F(\rho, \theta)$$

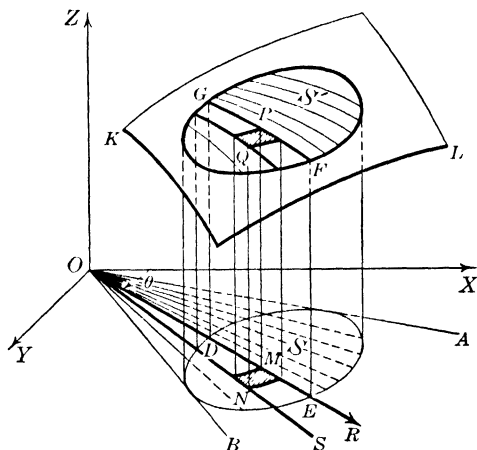
be the cylindrical equation of a surface, as KL in the figure. We wish to find the volume of the solid bounded above by this surface, below by the plane XOY , and laterally by the cylindrical surface whose right section by the plane XOY is the region S . This cylindrical surface intercepts on the surface (2) the region S' .

Divide the solid into elements of volume as follows:

Divide S into elements of area ΔA by drawing radial lines from O and arcs of circles about O , as in Art. 254. Pass planes through the radial lines and OZ . Pass cylindrical surfaces of revolution about OZ standing on the circular arcs within S . Then the solid is divided into columns such as $MNPQ$, where area $MN = \Delta A$, and $MP = z$. The element of volume is then a right prism with base ΔA and altitude z . Hence

$$(3) \quad \Delta V = z \Delta A.$$

The volume V is found by summing up the prisms (3) whose bases lie within S and finding the limit of this sum when the radial lines



and circular arcs within S increase in number so that $\Delta\rho \rightarrow 0$ and $\Delta\theta \rightarrow 0$. That is,

$$(4) \quad V = \lim_{\substack{\Delta\rho \rightarrow 0 \\ \Delta\theta \rightarrow 0}} \sum \sum z \Delta A.$$

We now show that the double limit in (4) may be found by successive integration. (Compare Art. 244.) This is done by finding the volume, approximately, of a slice of the solid included between two radial planes such as ROZ and SOZ , and then taking the limit of the sum of these slices.

Let $DEFG$ be the section of the solid in the plane ROZ . The values of z along the curve GPF are given by (2) when θ ($=$ angle XOR) is held fast. In the plane ROZ take OR and OZ as rectangular axes and (ρ, z) as coördinates. Let $(\bar{\rho}, \bar{z})$ be the centroid of area $DEFG$. Then by (2) and (3), Art. 177,

$$\bar{\rho} \cdot \text{area } DEFG = \int_{OD}^{OE} \rho z \, d\rho = \int_{OD}^{OE} \rho F(\rho, \theta) d\rho.$$

The integral will be a function of θ .

Now revolve area $DEFG$ about OZ . By Art. 250, the volume of the solid of revolution thus generated is $2\pi\bar{\rho} \cdot \text{area } DEFG$. The planes ROZ and SOZ cut out a wedge from this solid of revolution whose volume is $\Delta\theta\bar{\rho} \cdot \text{area } DEFG$, since angle $ROS = \Delta\theta$ (radians). Therefore

$$(5) \quad \Delta\theta \int_{OD}^{OE} \rho F(\rho, \theta) d\rho$$

is equal, approximately, to the volume of the slice of the solid included between the planes ROZ and SOZ . The limit of the sum of the wedges (5) when $\Delta\theta \rightarrow 0$ is the exact volume.

Hence

$$(6) \quad V = \int_{\alpha}^{\beta} \int_{\rho_1}^{\rho_2} F(\rho, \theta) \rho \, d\rho \, d\theta,$$

where $\alpha = \angle XOA$, $\beta = \angle XOB$, $\rho_1 = OD = f_1(\theta)$, $\rho_2 = OE = f_2(\theta)$, values to be found from the polar equations of the curves bounding S .

The element of the integral in (6), namely,

$$F(\rho, \theta) \rho \, d\rho \, d\theta = z\rho \, d\rho \, d\theta,$$

may be thought of as the volume of a right prism of altitude z and base of area $\rho \, d\rho \, d\theta$. Thus ΔA in (3) is replaced by $\rho \, \Delta\rho \, \Delta\theta$, as in Art. 254.

We have now the formula*

$$(M) \quad V = \iint_S z\rho \, d\rho \, d\theta = \iint_S F(\rho, \theta) \rho \, d\rho \, d\theta$$

*The order of integration is immaterial. Proof is omitted.

for the volume under the surface (2), and the limits are found as in Art. 254 for the area of the region S .

From (M) and (4) we may derive (2), Art. 254.

ILLUSTRATIVE EXAMPLE 1. Show that the volume of the solid bounded by the ellipsoid of revolution $b^2(x^2 + y^2) + a^2z^2 = a^2b^2$ and the cylindrical surface $x^2 + y^2 - ax = 0$ is given by

$$(7) \quad V = 4 \frac{b}{a} \int_0^{\frac{1}{2}\pi} \int_0^{a \cos \theta} \sqrt{a^2 - \rho^2} \rho \, d\rho \, d\theta.$$

Evaluate this integral.

Solution. By (1) the cylindrical equation of the ellipsoid is $b^2\rho^2 + a^2z^2 = a^2b^2$. Hence

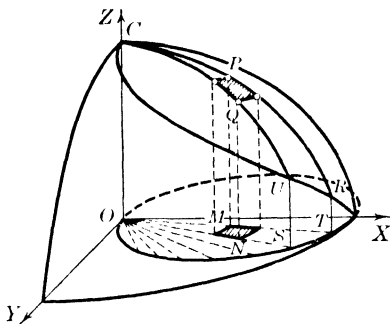
$$(8) \quad z = \frac{b}{a} \sqrt{a^2 - \rho^2}.$$

The polar equation of the circle $x^2 + y^2 - ax = 0$ in the XY -plane bounding S is, by (1),

$$(9) \quad \rho = a \cos \theta.$$

For the semicircle the limits for ρ are zero and $a \cos \theta$, when θ is held fast, and for θ , zero and $\frac{1}{2}\pi$. Substituting in (M) the value of z from (8) and the above limits, we get (7). Integrating,

$$V = \frac{4}{3} a^2 b (3\pi - 4) = 1.206 a^2 b.$$



Volume by triple integration. The element of volume ΔV will now be an *element* of the right prism used above in (3), that is, a right prism with base ΔA and altitude Δz . The solid is divided into such elements by passing through it the planes and cylindrical surfaces used in the figure at the beginning of this article and also planes parallel to the plane XOY at distances apart equal to Δz . We now have

$$(10) \quad \Delta V = \Delta z \Delta A.$$

By summation and taking the limit when $\Delta z \rightarrow 0$, $\Delta \rho \rightarrow 0$, $\Delta \theta \rightarrow 0$, we have

$$(N) \quad V = \iiint \rho \, dz \, d\rho \, d\theta,$$

for ΔA may be replaced by $\rho \Delta \rho \Delta \theta$ as before.

Formulas (3) in Art. 257 for the centroid become

$$V\bar{x} = \iiint \rho^2 \cos \theta \, dz \, d\rho \, d\theta, \quad V\bar{y} = \iiint \rho^2 \sin \theta \, dz \, d\rho \, d\theta,$$

$$V\bar{z} = \iiint \rho z \, dz \, d\rho \, d\theta,$$

when cylindrical coördinates are used.

ILLUSTRATIVE EXAMPLE 2. Find the volume of the solid whose upper surface is on the sphere

$$(11) \quad x^2 + y^2 + z^2 = 8$$

and whose lower surface is on the paraboloid of revolution

$$(12) \quad x^2 + y^2 = 2z.$$

Solution. The figure shows the sphere and the paraboloid in the first octant. The curve of intersection AB lies in the plane $z = 2$. Its projection DE on the XY -plane is the circle

$$(13) \quad x^2 + y^2 = 4.$$

The cylindrical equations are, by (1):

$$(14) \quad \rho^2 + z^2 = 8 \text{ (the sphere (11));}$$

$$(15) \quad \rho^2 = 2z \text{ (the paraboloid (12));}$$

$$(16) \quad \rho = 2 \text{ (the circle (13)).}$$

An element of area ΔA in the circle (16) is drawn at $M(\rho, \theta)$ in the figure. An element of volume ΔV is shown at $P(\rho, \theta, z)$.

We have, by (N),

$$(17) \quad V = \int_0^{2\pi} \int_0^2 \int_{\frac{1}{2}\rho^2}^{\sqrt{8-\rho^2}} \rho \, dz \, d\rho \, d\theta.$$

The limits are found as follows: Integrating with respect to z (holding ρ and θ fast), we sum up the elements of volume (10) in a column from the surface (15) to the surface (14) (MP_2 to MP_1 in the figure). From (15), $z = MP_2 = \frac{1}{2}\rho^2$; from (14), $z = MP_1 = \sqrt{8 - \rho^2}$, the z -limits. The limits for ρ and θ are those for the area of the circle (16). Integrating with respect to ρ gives the sum of the columns in the slice included between the plane passing through OZ and OM and the plane passing through OZ and ON . The final integration sums up these slices.

Integrating in (17),

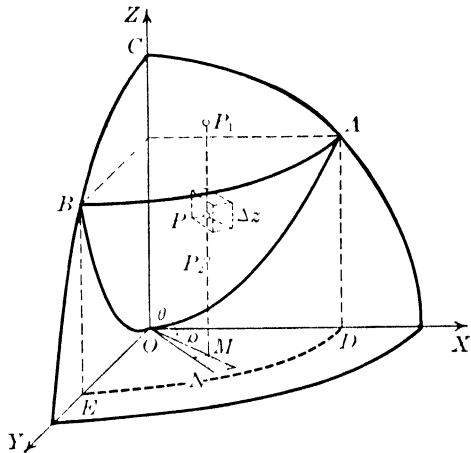
$$V = \frac{4}{3} \pi (8\sqrt{2} - 7) = 18.1. \text{ Ans.}$$

In the following problems, formulas (M) and (N) are to be used when the equations of bounding surfaces are in cylindrical coördinates (cylindrical equations). If the corresponding rectangular equations are needed for drawing a figure, they may be found by the transformation

$$(18) \quad \rho^2 = x^2 + y^2, \quad \theta = \arctan \frac{y}{x},$$

to which may be added

$$(19) \quad \sin \theta = \frac{y}{\sqrt{x^2 + y^2}}, \quad \cos \theta = \frac{x}{\sqrt{x^2 + y^2}}.$$



PROBLEMS

1. Find the volume of the solid below the cylindrical surface $x^2 + z = 4$, above the plane $x + z = 2$, and included between the planes $y = 0$, $y = 3$.

$$\text{Ans. } V = \int_0^3 \int_2^4 \int_{2-x}^{4-x^2} dz \, dx \, dy = 13\frac{1}{2} \text{ cubic units.}$$

2. Work out Illustrative Example 2, Art. 247, using cylindrical coordinates.

$$\text{Ans. } V = 2 \int_0^{\frac{1}{2}\pi} \int_0^{2a \cos \theta} \frac{\rho^3}{a} d\rho \, d\theta = \frac{3}{2} \pi a^3.$$

3. Find the volume of the solid bounded above by the cylinder $z = 4 - x^2$ and below by the elliptic paraboloid $z = 3x^2 + y^2$.

$$\text{Ans. } V = 4 \int_0^1 \int_0^{2\sqrt{1-x^2}} \int_{3x^2+y^2}^{4-x^2} dz \, dy \, dx = 4\pi.$$

4. Two planes forming an angle α radians with each other meet along a diameter of a sphere of radius a . Find the volume of the *spherical wedge* included between the planes and the spherical surface, using cylindrical coordinates.

$$\text{Ans. } \frac{2}{3} \alpha a^3.$$

5. Find the volume below the plane $z = x$ and above the elliptic paraboloid $z = x^2 + y^2$.

$$\text{Ans. } \frac{1}{32} \pi.$$

6. Work Problem 5 using cylindrical coordinates.

$$\text{Ans. } V = 2 \int_0^{\frac{1}{2}\pi} \int_0^{\cos \theta} \int_{\rho^2}^{\rho \cos \theta} \rho \, dz \, d\rho \, d\theta = \frac{1}{32} \pi.$$

7. Find the volume bounded by the sphere $\rho^2 + z^2 = a^2$ within the cylinder $\rho = a \cos \theta$.

$$\text{Ans. } \frac{2}{3} a^3 (\pi - \frac{4}{3}).$$

8. Find the volume above $z = 0$, below the cone $z^2 = x^2 + y^2$, and within the cylinder $x^2 + y^2 = 2ax$, using cylindrical coordinates.

$$\text{Ans. } \frac{32}{9} a^3.$$

9. Find the volume of the solid bounded by $z = x + 1$ and $2z = x^2 + y^2$.

$$\text{Ans. } \frac{9}{4} \pi.$$

10. In Problem 3 show that integration with respect to z gives (without further integration) $V = 4A - 4I_y - I_x$, where A is the area of the ellipse $4x^2 + y^2 = 4$, and I_x and I_y are moments of inertia for this ellipse as given by (E), Art. 252.

11. Find the volume below the plane $2z = 4 + \rho \cos \theta$, above $z = 0$, and within the cylinder $\rho = 2 \cos \theta$.

$$\text{Ans. } \frac{5}{2} \pi.$$

12. A solid is bounded by the paraboloid of revolution $az = \rho^2$ and the plane $z = c$. Find the centroid.

$$\text{Ans. } (0, 0, \frac{2}{3}c).$$

13. A solid is bounded by the hyperboloid $z^2 = a^2 + \rho^2$ and the upper nappe of the cone $z^2 = 2\rho^2$. Find the volume.

$$\text{Ans. } \frac{2}{3} \pi a^3 (\sqrt{2} - 1).$$

14. Find the centroid of the solid in Problem 13.

$$\text{Ans. } (0, 0, \frac{3}{8} a(\sqrt{2} + 1)).$$

15. Find the centroid of the solid in Problem 1. *Ans.* $(\frac{1}{2}, \frac{3}{2}, \frac{1}{5})$.
16. Find the centroid of the solid in Problem 2. *Ans.* $(\frac{1}{3}a, 0, \frac{1}{6}a)$.
17. Find the centroid of the solid in Problem 8.
18. Find the volume of the solid bounded below by $z = 0$, above by the cone $z = a - \rho$, and laterally by $\rho = a \cos \theta$. *Ans.* $\frac{1}{36}a^3(9\pi - 16)$.
19. Find the centroid of the solid in the preceding problem.
20. Find the volume of the solid below the spherical surface $\rho^2 + z^2 = 25$ and above the upper nappe of the conical surface $z = \rho + 1$.
21. Compare Illustrative Example 3, Art. 165, and Illustrative Example 1, Art. 257, and derive (N), Art. 165, from (L), Art. 257.
22. Derive formula (2), Art. 178, from the first formula in (3), Art. 257.

ADDITIONAL PROBLEMS

1. Find the volume bounded above by the sphere $\rho^2 + z^2 = r^2$, below by the cone $z = \rho \cot \phi$, and included between the planes $\theta = \beta$, $\theta = \beta + \Delta\beta$, ϕ and β being acute angles. (The solid is part of a spherical wedge, like $O-SQ'N$ in the figure of Art. 222 when OQ is drawn.)

$$\text{Ans. } \frac{1}{3} r^3 \Delta\beta(1 - \cos \phi).$$

2. Find (without integration) the volume bounded by the sphere $\rho^2 + z^2 = r^2$, the cones $z = \rho \cot \phi$, $z = \rho \cot(\phi + \Delta\phi)$, and the planes $\theta = \beta$, $\theta = \beta + \Delta\beta$, using the result in the preceding problem. (The solid is like $O-P_1RQS$ in the figure of Art. 222 when OR and OQ are drawn.)

$$\text{Ans. } \frac{2}{3} r^3 \Delta\beta \sin(\phi + \frac{1}{2} \Delta\phi) \sin \frac{1}{2} \Delta\phi.$$

3. Find (without integration) the volume bounded by $z = \rho \cot \phi$, $z = \rho \cot(\phi + \Delta\phi)$, $\theta = \beta$, $\theta = \beta + \Delta\beta$, and included between the spheres $\rho^2 + z^2 = r^2$, $\rho^2 + z^2 = (r + \Delta r)^2$, using the answer in Problem 2.

Ans. $2 \Delta\beta \Delta r \sin(\phi + \frac{1}{2} \Delta\phi) \sin \frac{1}{2} \Delta\phi (r^2 + r \Delta r + \frac{1}{3} \Delta r^2)$.
(The solid is obtained from the figure in Art. 222 by producing each of the radii OP_1 , OR , OQ , OS a distance Δr to P_1' , R' , Q' , S' on the sphere $\rho^2 + z^2 = (r + \Delta r)^2$. The cones intersect this sphere in the circular arcs $P_1'R'$ and $Q'S'$, and the planes in the arcs of great circles $P_1'S'$, $R'Q'$. The solid has the vertices P_1RQS - $P_1'R'Q'S'$.)

4. The solid of Problem 3 is the element of volume ΔV when spherical coördinates (8), p. 6, are used. Replace β by θ . Then one vertex P of ΔV has the spherical coordinates (r, ϕ, θ) . Prove, from Problem 3,

$$\lim_{\substack{\Delta r \rightarrow 0 \\ \Delta\theta \rightarrow 0 \\ \Delta\phi \rightarrow 0}} \frac{\Delta V}{r^2 \sin \phi \Delta r \Delta\phi \Delta\theta} = 1.$$

Therefore ΔV differs from $r^2 \sin \phi \Delta r \Delta\phi \Delta\theta$ by an infinitesimal of higher order (Art. 99).

5. In the solid of the preceding problem prove that the edges of ΔV meeting at any vertex are mutually perpendicular, and that the lengths of those intersecting at (r, ϕ, θ) are, respectively, Δr , $r \Delta \phi$, $r \sin \phi \Delta \theta$.

6. Describe the three systems of surfaces (spheres, cones, planes) which must be drawn to divide a solid R into elements of volume ΔV (Problem 4) when spherical coordinates are used. Let (r, ϕ, θ) be any point of ΔV . Then we write

$$\lim_{\substack{\Delta r \rightarrow 0 \\ \Delta \phi \rightarrow 0 \\ \Delta \theta \rightarrow 0}} \sum \sum \sum F(r, \phi, \theta) \Delta V = \iiint_R F(r, \phi, \theta) r^2 \sin \phi \, dr \, d\phi \, d\theta.$$

In the left-hand member ΔV may be replaced by $r^2 \sin \phi \, \Delta r \, \Delta \phi \, \Delta \theta$ (see Problem 4), that is, by the product of the three edges in Problem 5. The right-hand member is calculated by successive integration. (Proof omitted.)

7. Work out the integral in the preceding problem if $F(r, \phi, \theta) = r$, and R is the sphere $r = 2a \cos \phi$, that is, $x^2 + y^2 + z^2 = 2az$.

$$\text{Ans. } \int_0^{2\pi} \int_0^{\frac{1}{2}\pi} \int_0^{2a \cos \phi} r^3 \sin \phi \, dr \, d\phi \, d\theta = \frac{8}{5} \pi a^4.$$

8. Work out the integral in Problem 6 if $F(r, \phi, \theta) = r^2 \cos \phi$ and R is the region $r = 2a \cos \phi$.

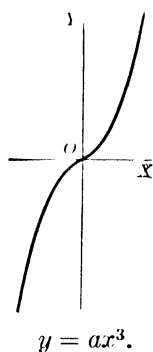
$$\text{Ans. } \frac{64}{35} \pi a^5.$$

CHAPTER XXVI

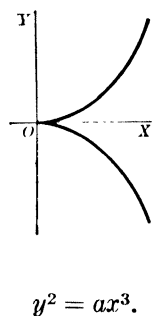
CURVES FOR REFERENCE

For the convenience of the student a number of the more common curves employed in the text are collected here.

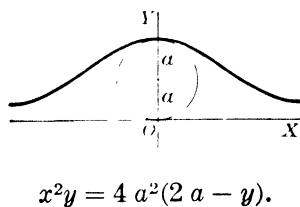
CUBICAL PARABOLA



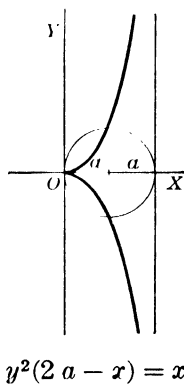
SEMICUBICAL PARABOLA



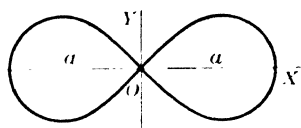
THE WITCH OF AGNESI



THE CISSOID OF DIOCLES



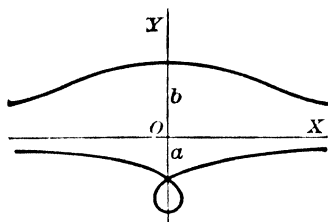
THE LEMNISCATE OF BERNOULLI



$$(x^2 + y^2)^2 = a^2(x^2 - y^2),$$

$$\rho^2 = a^2 \cos 2\theta.$$

THE CONCHOID OF NICOMEDES

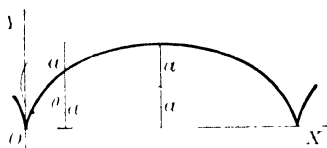


$$x^2 y^2 = (y + a)^2 (b^2 - y^2),$$

$$\rho = a \csc \theta + b.$$

(In the figure, $b > a$.)

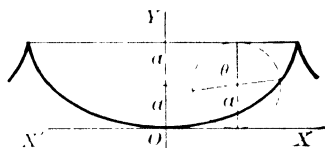
CYCLOID, ORDINARY CASE



$$x = a \text{ are vers } \frac{y}{a} - \sqrt{2ay - y^2}.$$

$$\begin{cases} x = a(\theta - \sin \theta), \\ y = a(1 - \cos \theta). \end{cases}$$

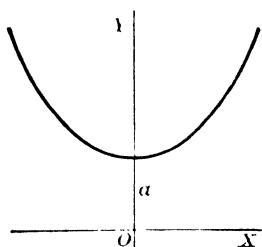
CYCLOID, VERTEX AT ORIGIN



$$x = a \text{ are vers } \frac{y}{a} + \sqrt{2ay - y^2}$$

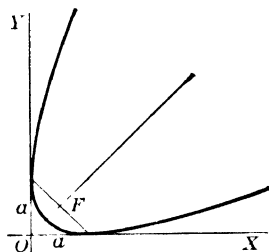
$$\begin{cases} x = a(\theta + \sin \theta), \\ y = a(1 - \cos \theta). \end{cases}$$

CATENARY



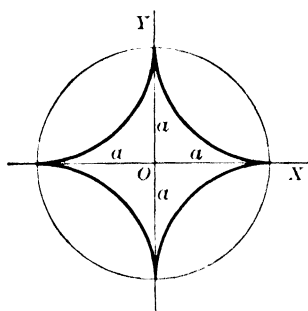
$$y = \frac{a}{2} \left(e^{\frac{x}{a}} + e^{-\frac{x}{a}} \right) = a \cosh \frac{x}{a}.$$

PARABOLA



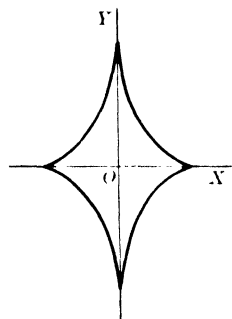
$$x^{\frac{1}{2}} + y^{\frac{1}{2}} = a^{\frac{1}{2}}.$$

HYPOCYCLOID OF FOUR CUSPS (ASTROID)



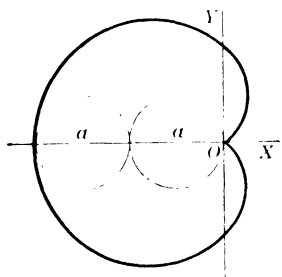
$$\begin{aligned} x^{\frac{2}{3}} + y^{\frac{2}{3}} &= a^{\frac{2}{3}}, \\ \begin{cases} x = a \cos^3 \theta, \\ y = a \sin^3 \theta. \end{cases} \end{aligned}$$

EVOLUTE OF ELLIPSE



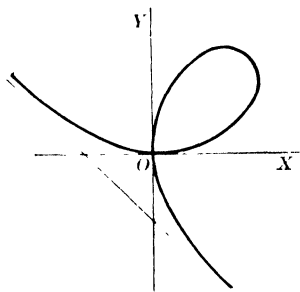
$$\begin{aligned} (ax)^{\frac{2}{3}} + (by)^{\frac{2}{3}} &= (a^2 - b^2)^{\frac{2}{3}}, \\ \begin{cases} x = a \cos^3 \theta, \\ y = b \sin^3 \theta. \end{cases} \end{aligned}$$

CARDIOID



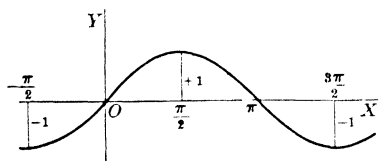
$$\begin{aligned} x^2 + y^2 + ax &= a \sqrt{x^2 + y^2}, \\ \rho &= a(1 - \cos \theta). \end{aligned}$$

FOLIUM OF DESCARTES



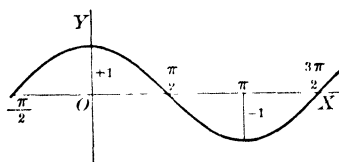
$$x^3 + y^3 - 3axy = 0.$$

SINE CURVE



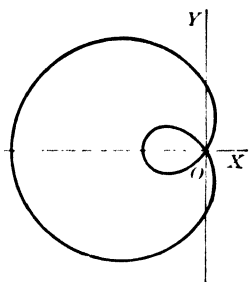
$$y = \sin x.$$

COSINE CURVE



$$y = \cos x.$$

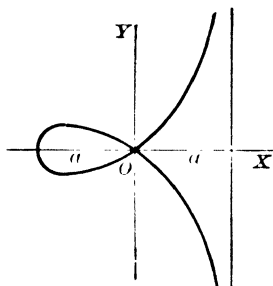
LIMAÇON



$$\rho = b - a \cos \theta.$$

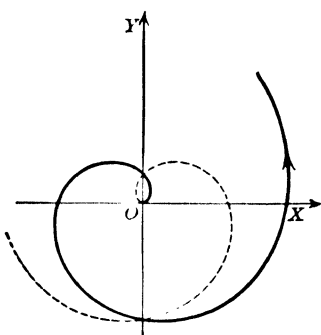
(In the figure, $b > a$.)

STROPHOID



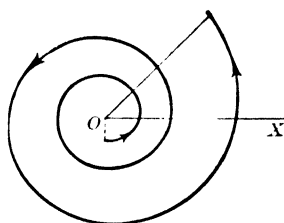
$$y^2 = x^2 \frac{a+x}{a-x}.$$

SPIRAL OF ARCHIMEDES



$$\rho = a\theta.$$

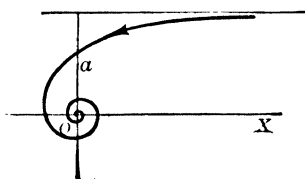
LOGARITHMIC OR EQUIANGULAR SPIRAL



$$\rho = e^{a\theta}, \text{ or}$$

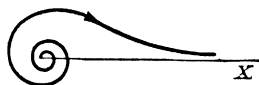
$$\log \rho = a\theta.$$

HYPERBOLIC OR RECIPROCAL SPIRAL



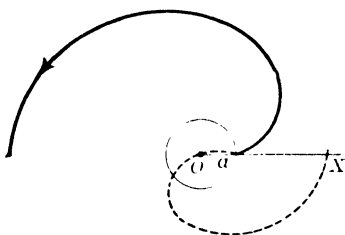
$$\rho\theta = a.$$

LITUUS



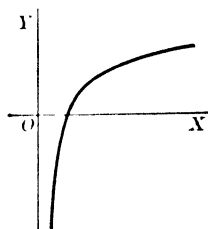
$$\rho^2\theta = a^2.$$

PARABOLIC SPIRAL



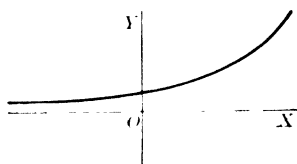
$$(\rho - a)^2 = 4ac\theta.$$

LOGARITHMIC CURVE



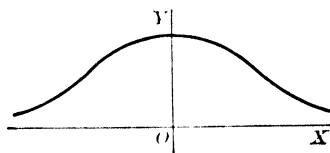
$$y = \log x.$$

EXPONENTIAL CURVE



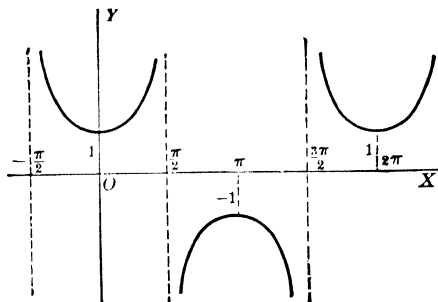
$$y = e^x.$$

PROBABILITY CURVE



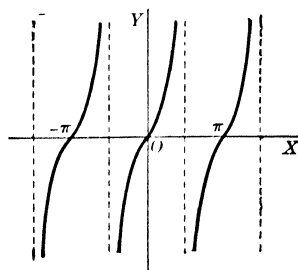
$$y = e^{-x^2}.$$

SECANT CURVE



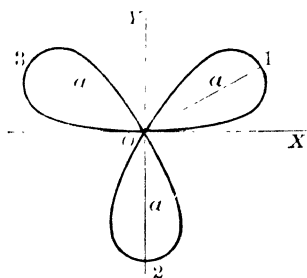
$$y = \sec x.$$

TANGENT CURVE



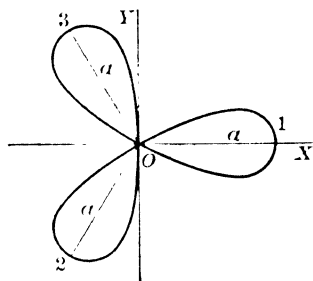
$$y = \tan x.$$

THREE-LEAVED ROSE



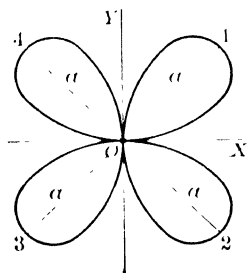
$$\rho = a \sin 3 \theta.$$

THREE-LEAVED ROSE



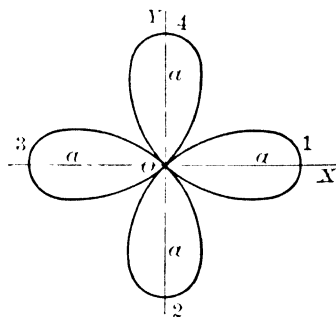
$$\rho = a \cos 3 \theta.$$

FOUR-LEAVED ROSE



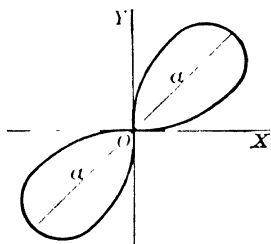
$$\rho = a \sin 2 \theta.$$

FOUR-LEAVED ROSE



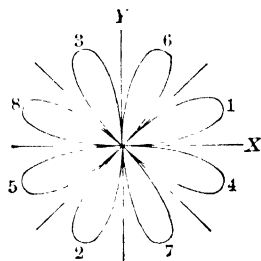
$$\rho = a \cos 2 \theta.$$

TWO-LEAVED ROSE LEMNISCATE



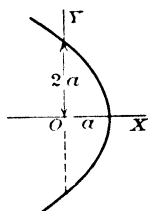
$$\rho^2 = a^2 \sin 2 \theta.$$

EIGHT-LEAVED ROSE



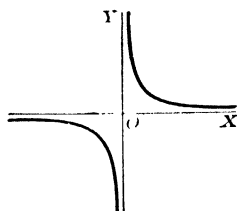
$$\rho = a \sin 4 \theta.$$

PARABOLA



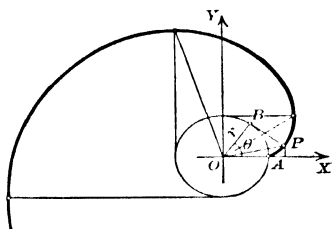
$$\rho = a \sec^2 \frac{\theta}{2}.$$

EQUILATERAL HYPERBOLA



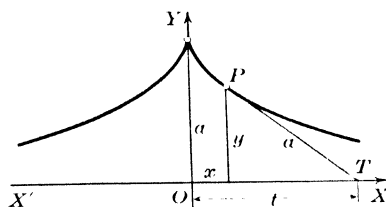
$$xy = a.$$

INVOLUTE OF A CIRCLE



$$\begin{cases} x = r \cos \theta + r\theta \sin \theta, \\ y = r \sin \theta - r\theta \cos \theta. \end{cases}$$

TRACTRIX



$$x = a \operatorname{sech}^{-1} \frac{y}{a} - \sqrt{a^2 - y^2}.$$

$$\begin{cases} x = t - a \tanh \frac{t}{a}, \\ y = a \operatorname{sech} \frac{t}{a}. \end{cases}$$

CHAPTER XXVII

TABLE OF INTEGRALS

Some Elementary Forms

$$1. \int df(x) = \int f'(x) dx = f(x) + C.$$

$$2. \int a du = a \int du.$$

$$3. \int (du \pm dv \pm dw \pm \dots) = \int du \pm \int dv \pm \int dw \pm \dots.$$

$$4. \int u^n du = \frac{u^{n+1}}{n+1} + C. \quad (n \neq -1)$$

$$5. \int \frac{du}{u} = \ln u + C.$$

Rational Forms containing $a + bu$

See also the Binomial Reduction Formulas 96-104.

$$6. \int (a + bu)^n du = \frac{(a + bu)^{n+1}}{b(n+1)} + C. \quad (n \neq -1)$$

$$7. \int \frac{du}{a + bu} = \frac{1}{b} \ln (a + bu) + C.$$

$$8. \int \frac{u du}{a + bu} = \frac{1}{b^2} [a + bu - a \ln (a + bu)] + C.$$

$$9. \int \frac{u^2 du}{a + bu} = \frac{1}{b^3} [\frac{1}{2}(a + bu)^2 - 2a(a + bu) + a^2 \ln (a + bu)] + C.$$

$$10. \int \frac{u du}{(a + bu)^2} = \frac{1}{b^2} \left[\frac{a}{a + bu} + \ln (a + bu) \right] + C.$$

$$11. \int \frac{u^2 du}{(a + bu)^2} = \frac{1}{b^3} \left[a + bu - \frac{a^2}{a + bu} - 2a \ln (a + bu) \right] + C.$$

$$12. \int \frac{u du}{(a + bu)^3} = \frac{1}{b^2} \left[-\frac{1}{a + bu} + \frac{a}{2(a + bu)^2} \right] + C.$$

$$13. \int \frac{du}{u(a + bu)} = -\frac{1}{a} \ln \left(\frac{a + bu}{u} \right) + C.$$

$$14. \int \frac{du}{u^2(a + bu)} = -\frac{1}{au} + \frac{b}{a^2} \ln \left(\frac{a + bu}{u} \right) + C.$$

$$15. \int \frac{du}{u(a + bu)^2} = \frac{1}{a(a + bu)} - \frac{b}{a^2} \ln \left(\frac{a + bu}{u} \right) + C.$$

Rational Forms containing $a^2 \pm b^2 u^2$

16. $\int \frac{du}{a^2 + b^2 u^2} = \frac{1}{ab} \arctan \frac{bu}{a} + C.$
17. $\int \frac{du}{a^2 - b^2 u^2} = \frac{1}{2ab} \ln \left(\frac{a+bu}{a-bu} \right) + C. \quad (a^2 > b^2 u^2)$
 $\int \frac{du}{b^2 u^2 - a^2} = \frac{1}{2ab} \ln \left(\frac{bu-a}{bu+a} \right) + C. \quad (a^2 < b^2 u^2)$
18. $\int u(a^2 \pm b^2 u^2)^n du = \frac{(a^2 \pm b^2 u^2)^{n+1}}{\pm 2b^2(n+1)} + C. \quad (n \neq -1)$
19. $\int \frac{u du}{a^2 \pm b^2 u^2} = \frac{1}{\pm 2b^2} \ln(a^2 \pm b^2 u^2) + C.$
20. $\int \frac{u^m du}{(a^2 \pm b^2 u^2)^p} = \frac{u^{m+1}}{\pm b^2(m-2p+1)(a^2 \pm b^2 u^2)^{p-1}} - \frac{a^2(m-1)}{\pm b^2(m-2p+1)} \int \frac{u^{m-2} du}{(a^2 \pm b^2 u^2)^p}.$
21. $\int \frac{u^m du}{(a^2 \pm b^2 u^2)^p} = \frac{u^{m+1}}{2a^2(p-1)(a^2 \pm b^2 u^2)^{p-1}} - \frac{m-2p+3}{2a^2(p-1)} \int \frac{u^m du}{(a^2 \pm b^2 u^2)^{p-1}}.$
22. $\int \frac{du}{u(a^2 \pm b^2 u^2)} = \frac{1}{2a^2} \ln \left(\frac{u^2}{a^2 \pm b^2 u^2} \right) + C.$
23. $\int \frac{du}{u^m(a^2 \pm b^2 u^2)^p} = -\frac{1}{a^2(m-1)u^{m-1}(a^2 \pm b^2 u^2)^{p-1}} - \frac{\pm b^2(m+2p-3)}{a^2(m-1)} \int \frac{du}{u^{m-2}(a^2 \pm b^2 u^2)^p}.$
24. $\int \frac{du}{u^m(a^2 \pm b^2 u^2)^p} = \frac{1}{2a^2(p-1)u^{m-1}(a^2 \pm b^2 u^2)^{p-1}} + \frac{m+2p-3}{2a^2(p-1)} \int \frac{du}{u^m(a^2 \pm b^2 u^2)^{p-1}}.$

Forms containing $\sqrt{a+bu}$

The integrand may be rationalized by setting $a+bu=v^2$. See also the Binomial Reduction Formulas 96-104.

25. $\int u \sqrt{a+bu} du = -\frac{2(2a-3bu)(a+bu)^{\frac{3}{2}}}{15b^2} + C.$
26. $\int u^2 \sqrt{a+bu} du = \frac{2(8a^2-12abu+15b^2u^2)(a+bu)^{\frac{3}{2}}}{105b^3} + C.$
27. $\int u^m \sqrt{a+bu} du = \frac{2u^m(a+bu)^{\frac{3}{2}}}{b(2m+3)} - \frac{2am}{b(2m+3)} \int u^{m-1} \sqrt{a+bu} du.$
28. $\int \frac{u du}{\sqrt{a+bu}} = -\frac{2(2a-bu)\sqrt{a+bu}}{3b^2} + C.$

$$29. \int \frac{u^2 du}{\sqrt{a+bu}} = \frac{2(8a^2 - 4abu + 3b^2u^2)\sqrt{a+bu}}{15b^3} + C.$$

$$30. \int \frac{u^m du}{\sqrt{a+bu}} = \frac{2u^m\sqrt{a+bu}}{b(2m+1)} - \frac{2am}{b(2m+1)} \int \frac{u^{m-1} du}{\sqrt{a+bu}}.$$

$$31. \int \frac{du}{u\sqrt{a+bu}} = \frac{1}{\sqrt{a}} \ln \left(\frac{\sqrt{a+bu} - \sqrt{a}}{\sqrt{a+bu} + \sqrt{a}} \right) + C, \text{ for } a > 0.$$

$$32. \int \frac{du}{u\sqrt{a+bu}} = \frac{2}{\sqrt{-a}} \operatorname{arc tan} \sqrt{\frac{a+bu}{-a}} + C, \text{ for } a < 0.$$

$$33. \int \frac{du}{u^m\sqrt{a+bu}} = -\frac{\sqrt{a+bu}}{a(m-1)u^{m-1}} - \frac{b(2m-3)}{2a(m-1)} \int \frac{du}{u^{m-1}\sqrt{a+bu}}.$$

$$34. \int \frac{\sqrt{a+bu} du}{u} = 2\sqrt{a+bu} + a \int \frac{du}{u\sqrt{a+bu}}.$$

$$35. \int \frac{\sqrt{a+bu} du}{u^m} = -\frac{(a+bu)^{\frac{3}{2}}}{a(m-1)u^{m-1}} - \frac{b(2m-5)}{2a(m-1)} \int \frac{\sqrt{a+bu} du}{u^{m-1}}.$$

Forms containing $\sqrt{u^2 \pm a^2}$

In this group of formulas we may replace

$$\ln(u + \sqrt{u^2 + a^2}) \quad \text{by} \quad \sinh^{-1} \frac{u}{a},$$

$$\ln(u + \sqrt{u^2 - a^2}) \quad \text{by} \quad \cosh^{-1} \frac{u}{a},$$

$$\ln\left(\frac{a + \sqrt{u^2 + a^2}}{u}\right) \quad \text{by} \quad \sinh^{-1} \frac{a}{u}.$$

$$36. \int (u^2 \pm a^2)^{\frac{1}{2}} du = \frac{n}{2} \sqrt{u^2 \pm a^2} \pm \frac{a^2}{2} \ln(u + \sqrt{u^2 \pm a^2}) + C.$$

$$37. \int (u^2 \pm a^2)^{\frac{n}{2}} du = \frac{n(u^2 \pm a^2)^{\frac{n}{2}}}{n+1} \pm \frac{na^2}{n+1} \int (u^2 \pm a^2)^{\frac{n}{2}-1} du. \quad (n \neq -1)$$

$$38. \int u(u^2 \pm a^2)^{\frac{n}{2}} du = \frac{(u^2 \pm a^2)^{\frac{n}{2}+1}}{n+2} + C. \quad (n \neq -2)$$

$$39. \int u^m (u^2 \pm a^2)^{\frac{n}{2}} du = \frac{u^{m+1} (u^2 \pm a^2)^{\frac{n}{2}+1}}{n+m+1} - \frac{\pm a^2(m+1)}{n+m+1} \int u^{m-2} (u^2 \pm a^2)^{\frac{n}{2}} du.$$

$$40. \int \frac{du}{(u^2 \pm a^2)^{\frac{3}{2}}} = \ln(u + \sqrt{u^2 \pm a^2}) + C.$$

$$41. \int \frac{du}{(u^2 \pm a^2)^{\frac{3}{2}}} = \frac{u}{\pm a^2 \sqrt{u^2 \pm a^2}} + C.$$

- $$42. \int \frac{u \, du}{(u^2 \pm a^2)^{\frac{n}{2}}} = \frac{(u^2 \pm a^2)^{1-\frac{n}{2}}}{2-n} + C.$$
- $$43. \int \frac{u^2 \, du}{(u^2 \pm a^2)^{\frac{1}{2}}} = \frac{u}{2} \sqrt{u^2 \pm a^2} - \frac{\pm a^2}{2} \ln(u + \sqrt{u^2 \pm a^2}) + C.$$
- $$44. \int \frac{u^2 \, du}{(u^2 \pm a^2)^{\frac{1}{2}}} = -\frac{u}{\sqrt{u^2 \pm a^2}} + \ln(u + \sqrt{u^2 \pm a^2}) + C.$$
- $$45. \int \frac{u^m \, du}{(u^2 \pm a^2)^{\frac{n}{2}}} = \frac{u^{m-1}}{(m-n+1)(u^2 \pm a^2)^{\frac{n}{2}-1}} - \frac{\pm a^2(m-1)}{m-n+1} \int \frac{u^{m-2} \, du}{(u^2 \pm a^2)^{\frac{n}{2}}}.$$
- $$46. \int \frac{u^m \, du}{(u^2 \pm a^2)^{\frac{n}{2}}} = \frac{u^{m+1}}{\pm a^2(n-2)(u^2 \pm a^2)^{\frac{n}{2}-1}} - \frac{m-n+3}{\pm a^2(n-2)} \int \frac{u^m \, du}{(u^2 \pm a^2)^{\frac{n}{2}-1}}.$$
- $$47. \int \frac{du}{u(u^2 + a^2)^{\frac{1}{2}}} = -\frac{1}{a} \ln\left(\frac{a + \sqrt{u^2 + a^2}}{u}\right) + C.$$
- $$48. \int \frac{du}{u(u^2 - a^2)^{\frac{1}{2}}} = \frac{1}{a} \operatorname{arc} \sec \frac{u}{a} + C.$$
- $$49. \int \frac{du}{u^2(u^2 \pm a^2)^{\frac{1}{2}}} = -\frac{\sqrt{u^2 \pm a^2}}{\pm a^2 u} + C.$$
- $$50. \int \frac{du}{u^3(u^2 + a^2)^{\frac{1}{2}}} = -\frac{\sqrt{u^2 + a^2}}{2a^2 u^2} + \frac{1}{2a^3} \ln\left(\frac{a + \sqrt{u^2 + a^2}}{u}\right) + C.$$
- $$51. \int \frac{du}{u^3(u^2 - a^2)^{\frac{1}{2}}} = \frac{\sqrt{u^2 - a^2}}{2a^2 u^2} + \frac{1}{2a^3} \operatorname{arc} \sec \frac{u}{a} + C.$$
- $$52. \int \frac{du}{u^m(u^2 \pm a^2)^{\frac{n}{2}}} = -\frac{1}{\pm a^2(m-1)u^{m-1}(u^2 \pm a^2)^{\frac{n}{2}-1}} - \frac{m+n-3}{\pm a^2(m-1)} \int \frac{du}{u^{m-2}(u^2 \pm a^2)^{\frac{n}{2}}}.$$
- $$53. \int \frac{du}{u^m(u^2 \pm a^2)^{\frac{n}{2}}} = \frac{1}{\pm a^2(n-2)u^{m-1}(u^2 \pm a^2)^{\frac{n}{2}-1}} + \frac{m+n-3}{\pm a^2(n-2)} \int \frac{du}{u^m(u^2 \pm a^2)^{\frac{n}{2}-1}}.$$
- $$54. \int \frac{(u^2 + a^2)^{\frac{1}{2}} du}{u} = \sqrt{u^2 + a^2} - a \ln\left(\frac{a + \sqrt{u^2 + a^2}}{u}\right) + C.$$
- $$55. \int \frac{(u^2 - a^2)^{\frac{1}{2}} du}{u} = \sqrt{u^2 - a^2} - a \operatorname{arc} \sec \frac{u}{a} + C.$$

$$56. \int \frac{(u^2 \pm a^2)^{\frac{1}{2}} du}{u^2} = -\frac{\sqrt{u^2 \pm a^2}}{u} + \ln(u + \sqrt{u^2 \pm a^2}) + C.$$

$$57. \int \frac{(u^2 \pm a^2)^{\frac{n}{2}} du}{u^m} = -\frac{(u^2 \pm a^2)^{\frac{n}{2}+1}}{\pm a^2(m-1)u^{m-1}} \\ - \frac{m-n-3}{\pm a^2(m-1)} \int \frac{(u^2 \pm a^2)^{\frac{n}{2}} du}{u^{m-2}}.$$

$$58. \int \frac{(u^2 \pm a^2)^{\frac{n}{2}} du}{u^m} = \frac{(u^2 \pm a^2)^{\frac{n}{2}}}{(n-m+1)u^{m-1}} + \frac{\pm a^2 n}{n-m+1} \int \frac{(u^2 \pm a^2)^{\frac{n}{2}-1} du}{u^m}.$$

Forms containing $\sqrt{a^2 - u^2}$

$$59. \int (a^2 - u^2)^{\frac{1}{2}} du = \frac{u}{2} \sqrt{a^2 - u^2} + \frac{a^2}{2} \arcsin \frac{u}{a} + C.$$

$$60. \int (a^2 - u^2)^{\frac{n}{2}} du = \frac{u(a^2 - u^2)^{\frac{n}{2}}}{n+1} + \frac{a^2 n}{n+1} \int (a^2 - u^2)^{\frac{n}{2}-1} du, \quad (n \neq -1)$$

$$61. \int u(a^2 - u^2)^{\frac{n}{2}} du = -\frac{(a^2 - u^2)^{\frac{n}{2}+1}}{n+2} + C, \quad (n \neq -2)$$

$$62. \int u^m(a^2 - u^2)^{\frac{n}{2}} du = -\frac{u^{m+1}(a^2 - u^2)^{\frac{n}{2}+1}}{n+m+1} \\ + \frac{a^2(m-1)}{n+m+1} \int u^{m-2}(a^2 - u^2)^{\frac{n}{2}} du.$$

$$63. \int \frac{du}{(a^2 - u^2)^{\frac{1}{2}}} = \arcsin \frac{u}{a} + C.$$

$$64. \int \frac{du}{(a^2 - u^2)^{\frac{1}{2}}} = \frac{u}{a^2 \sqrt{a^2 - u^2}} + C.$$

$$65. \int \frac{u du}{(a^2 - u^2)^{\frac{n}{2}}} = \frac{(a^2 - u^2)^{1-\frac{n}{2}}}{n-2} + C.$$

$$66. \int \frac{u^2 du}{(a^2 - u^2)^{\frac{1}{2}}} = -\frac{u}{2} \sqrt{a^2 - u^2} + \frac{a^2}{2} \arcsin \frac{u}{a} + C.$$

$$67. \int \frac{u^2 du}{(a^2 - u^2)^{\frac{3}{2}}} = \frac{u}{\sqrt{a^2 - u^2}} - \arcsin \frac{u}{a} + C.$$

$$68. \int \frac{u^m du}{(a^2 - u^2)^{\frac{n}{2}}} = -\frac{u^{m-1}}{(m-n+1)(a^2 - u^2)^{\frac{n}{2}-1}} + \frac{a^2(m-1)}{m-n+1} \int \frac{u^{m-2} du}{(a^2 - u^2)^{\frac{n}{2}}}.$$

$$69. \int \frac{u^m du}{(a^2 - u^2)^{\frac{n}{2}}} = \frac{u^{m+1}}{a^2(n-2)(a^2 - u^2)^{\frac{n}{2}-1}} - \frac{m-n+3}{a^2(n-2)} \int \frac{u^m du}{(a^2 - u^2)^{\frac{n}{2}-1}}.$$

$$70. \int \frac{du}{u(a^2 - u^2)^{\frac{1}{2}}} = -\frac{1}{a} \ln \left(\frac{a + \sqrt{a^2 - u^2}}{u} \right) + C = -\frac{1}{a} \cosh^{-1} \frac{a}{u} + C.$$

$$71. \int \frac{du}{u^2(a^2 - u^2)^{\frac{1}{2}}} = -\frac{\sqrt{a^2 - u^2}}{a^2 u} + C.$$

$$72. \int \frac{du}{u^3(a^2 - u^2)^{\frac{1}{2}}} = -\frac{\sqrt{a^2 - u^2}}{2 a^2 u^2} - \frac{1}{2 a^3} \ln \left(\frac{a + \sqrt{a^2 - u^2}}{u} \right) + C \\ = -\frac{\sqrt{a^2 - u^2}}{2 a^2 u^2} - \frac{1}{2 a^3} \cosh^{-1} \frac{a}{u} + C.$$

$$73. \int \frac{du}{u^m(a^2 - u^2)^{\frac{n}{2}}} = -\frac{1}{a^2(m-1)u^{m-1}(a^2 - u^2)^{\frac{n}{2}-1}} \\ + \frac{m+n-3}{a^2(m-1)} \int \frac{du}{u^{m-2}(a^2 - u^2)^{\frac{n}{2}}}.$$

$$74. \int \frac{du}{u^m(a^2 - u^2)^{\frac{n}{2}}} = \frac{1}{a^2(n-2)u^{m-1}(a^2 - u^2)^{\frac{n}{2}-1}} \\ + \frac{m+n-3}{a^2(n-2)} \int \frac{du}{u^{m-1}(a^2 - u^2)^{\frac{n}{2}-1}}.$$

$$75. \int \frac{(a^2 - u^2)^{\frac{1}{2}} du}{u} = \sqrt{a^2 - u^2} - a \ln \left(\frac{a + \sqrt{a^2 - u^2}}{u} \right) + C \\ = \sqrt{a^2 - u^2} - a \cosh^{-1} \frac{a}{u} + C.$$

$$76. \int \frac{(a^2 - u^2)^{\frac{1}{2}} du}{u^2} = -\frac{\sqrt{a^2 - u^2}}{u} - \arcsin \frac{u}{a} + C.$$

$$77. \int \frac{(a^2 - u^2)^{\frac{n}{2}} du}{u^m} = -\frac{(a^2 - u^2)^{\frac{n}{2}+1}}{a^2(m-1)u^{m-1}} + \frac{m-n-3}{a^2(m-1)} \int \frac{(a^2 - u^2)^{\frac{n}{2}} du}{u^{m-2}}.$$

$$78. \int \frac{(a^2 - u^2)^{\frac{n}{2}} du}{u^m} = \frac{(a^2 - u^2)^{\frac{n}{2}}}{(n-m+1)u^{m-1}} + \frac{a^2 n}{n-m+1} \int \frac{(a^2 - u^2)^{\frac{n}{2}-1} du}{u^m}.$$

Forms containing $\sqrt{2au \pm u^2}$

The Binomial Reduction Formulas 96-104 may be applied by writing $\sqrt{2au \pm u^2} = u^{\frac{1}{2}}(2a \pm u)^{\frac{1}{2}}$.

$$79. \int \sqrt{2au - u^2} du = \frac{u-a}{2} \sqrt{2au - u^2} + \frac{a^2}{2} \arcsin \left(1 - \frac{u}{a} \right) + C.$$

$$80. \int u \sqrt{2au - u^2} du = -\frac{3a^2 + au - 2u^2}{6} \sqrt{2au - u^2} \\ + \frac{a^3}{2} \arcsin \left(1 - \frac{u}{a} \right) + C.$$

- $$81. \int u^m \sqrt{2au - u^2} du = -\frac{u^{m-1}(2au - u^2)^{\frac{3}{2}}}{m+2} + \frac{a(2m+1)}{m+2} \int u^{m-1} \sqrt{2au - u^2} du.$$
- $$82. \int \frac{\sqrt{2au - u^2} du}{u} = \sqrt{2au - u^2} + a \arccos\left(1 - \frac{u}{a}\right) + C.$$
- $$83. \int \frac{\sqrt{2au - u^2} du}{u^2} = -\frac{2\sqrt{2au - u^2}}{u} - \arccos\left(1 - \frac{u}{a}\right) + C.$$
- $$84. \int \frac{\sqrt{2au - u^2} du}{u^3} = -\frac{(2au - u^2)^{\frac{3}{2}}}{3au^3} + C.$$
- $$85. \int \frac{\sqrt{2au - u^2} du}{u^m} = -\frac{(2au - u^2)^{\frac{3}{2}}}{a(2m-3)u^m} + \frac{m-3}{a(2m-3)} \int \frac{\sqrt{2au - u^2} du}{u^{m-1}}.$$
- $$86. \int \frac{du}{\sqrt{2au - u^2}} = \arccos\left(1 - \frac{u}{a}\right) + C.$$
- $$87. \int \frac{du}{\sqrt{2au + u^2}} = \ln(u + a + \sqrt{2au + u^2}) + C.$$
- $$88. \int F(u, \sqrt{2au + u^2}) du = \int F(z - a, \sqrt{z^2 - a^2}) dz, \text{ where } z = u + a.$$
- $$89. \int \frac{u du}{\sqrt{2au - u^2}} = -\sqrt{2au - u^2} + a \arccos\left(1 - \frac{u}{a}\right) + C.$$
- $$90. \int \frac{u^2 du}{\sqrt{2au - u^2}} = -\frac{(u+3a)\sqrt{2au - u^2}}{2} + \frac{3a^2}{2} \arccos\left(1 - \frac{u}{a}\right) + C.$$
- $$91. \int \frac{u^m du}{\sqrt{2au - u^2}} = -\frac{u^{m-1}\sqrt{2au - u^2}}{m} + \frac{a(2m-1)}{m} \int \frac{u^{m-1} du}{\sqrt{2au - u^2}}.$$
- $$92. \int \frac{du}{u\sqrt{2au - u^2}} = -\frac{\sqrt{2au - u^2}}{au} + C.$$
- $$93. \int \frac{du}{u^m \sqrt{2au - u^2}} = -\frac{\sqrt{2au - u^2}}{a(2m-1)u^m} + \frac{m-1}{a(2m-1)} \int \frac{du}{u^{m-1} \sqrt{2au - u^2}}.$$
- $$94. \int \frac{du}{(2au - u^2)^{\frac{3}{2}}} = \frac{u-a}{a^2 \sqrt{2au - u^2}} + C.$$
- $$95. \int \frac{u du}{(2au - u^2)^{\frac{3}{2}}} = \frac{u}{a \sqrt{2au - u^2}} + C.$$

Binomial Reduction Formulas

$$96. \int u^m (a + bu^q)^p du = \frac{u^{m-q+1} (a + bu^q)^{p+1}}{b(pq + m + 1)} - \frac{a(m-q+1)}{b(pq + m + 1)} \int u^{m-q} (a + bu^q)^p du.$$

$$97. \int u^m (a + bu^q)^p du = \frac{u^{m+1} (a + bu^q)^p}{pq + m + 1} + \frac{apq}{pq + m + 1} \int u^m (a + bu^q)^{p-1} du.$$

$$98. \int \frac{du}{u^m (a + bu^q)^p} = -\frac{1}{a(m-1)u^{m-1} (a + bu^q)^{p-1}} - \frac{b(m-q+pq-1)}{a(m-1)} \int \frac{du}{u^m (a + bu^q)^p}.$$

$$99. \int \frac{du}{u^m (a + bu^q)^p} = \frac{1}{aq(p-1)u^{m-1} (a + bu^q)^{p-1}} + \frac{m-q+pq-1}{aq(p-1)} \int \frac{du}{u^m (a + bu^q)^{p-1}}.$$

$$100. \int \frac{du}{u(a + bu^q)} = \frac{1}{aq} \ln \left(\frac{u^q}{a + bu^q} \right) + C.$$

$$101. \int \frac{(a + bu^q)^p du}{u^m} = -\frac{(a + bu^q)^{p+1}}{a(m-1)u^{m-1}} - \frac{b(m-q-pq-1)}{a(m-1)} \int \frac{(a + bu^q)^p du}{u^{m-q}}.$$

$$102. \int \frac{(a + bu^q)^p du}{u^m} = \frac{(a + bu^q)^p}{(pq-m+1)u^{m-1}} + \frac{apq}{pq-m+1} \int \frac{(a + bu^q)^{p-1} du}{u^m}.$$

$$103. \int \frac{u^m du}{(a + bu^q)^p} = \frac{u^{m-q+1}}{b(m-pq+1)(a + bu^q)^{p-1}} - \frac{a(m-q+1)}{b(m-pq+1)} \int \frac{u^{m-q} du}{(a + bu^q)^p}.$$

$$104. \int \frac{u^m du}{(a + bu^q)^p} = \frac{u^{m+1}}{aq(p-1)(a + bu^q)^{p-1}} - \frac{m+q-pq+1}{aq(p-1)} \int \frac{u^m du}{(a + bu^q)^{p-1}}.$$

Forms containing $a + bu \pm cu^2$ ($c > 0$)

The expression $a + bu + cu^2$ may be reduced to a binomial by writing

$$u = z - \frac{b}{2c}, \quad k = \frac{b^2 - 4ac}{4c^2}.$$

$$\text{Then} \quad a + bu + cu^2 = c(z^2 - k).$$

The expression $a + bu - cu^2$ may be reduced to a binomial by writing

$$u = z + \frac{b}{2c}, \quad k = \frac{b^2 + 4ac}{4c^2}.$$

$$\text{Then} \quad a + bu - cu^2 = c(k - z^2).$$

$$105. \int \frac{du}{a + bu + cu^2} = \frac{2}{\sqrt{4ac - b^2}} \arctan \left(\frac{2cu + b}{\sqrt{4ac - b^2}} \right) + C, \quad \text{when } b^2 < 4ac.$$

$$106. \int \frac{du}{a + bu + cu^2} = \frac{1}{\sqrt{b^2 - 4ac}} \ln \left(\frac{2cu + b - \sqrt{b^2 - 4ac}}{2cu + b + \sqrt{b^2 - 4ac}} \right) + C,$$

when $b^2 > 4ac$.

$$107. \int \frac{du}{a + bu - cu^2} = \frac{1}{\sqrt{b^2 + 4ac}} \ln \left(\frac{\sqrt{b^2 + 4ac} + 2cu - b}{\sqrt{b^2 + 4ac} - 2cu + b} \right) + C.$$

$$108. \int \frac{(Mu + N)du}{a + bu \pm cu^2} = \frac{\pm M}{2c} \ln(a + bu \pm cu^2) \\ + \left(N \mp \frac{bM}{2c} \right) \int \frac{du}{a + bu \pm cu^2}.$$

$$109. \int \sqrt{a + bu + cu^2} du = \frac{2cu + b}{4c} \sqrt{a + bu + cu^2} \\ - \frac{b^2 - 4ac}{8c^{\frac{3}{2}}} \ln(2cu + b + 2\sqrt{c}\sqrt{a + bu + cu^2}) + C.$$

$$110. \int \sqrt{a + bu - cu^2} du = \frac{2cu - b}{4c} \sqrt{a + bu - cu^2} \\ + \frac{b^2 + 4ac}{8c^{\frac{3}{2}}} \arcsin \left(\frac{2cu - b}{\sqrt{b^2 + 4ac}} \right) + C.$$

$$111. \int \frac{du}{\sqrt{a + bu + cu^2}} = \frac{1}{\sqrt{c}} \ln(2cu + b + 2\sqrt{c}\sqrt{a + bu + cu^2}) + C.$$

$$112. \int \frac{du}{\sqrt{a + bu - cu^2}} = \frac{1}{\sqrt{c}} \arcsin \left(\frac{2cu - b}{\sqrt{b^2 + 4ac}} \right) + C.$$

$$113. \int \frac{u du}{\sqrt{a + bu + cu^2}} = \frac{\sqrt{a + bu + cu^2}}{c} \\ - \frac{b}{2c^{\frac{3}{2}}} \ln(2cu + b + 2\sqrt{c}\sqrt{a + bu + cu^2}) + C.$$

$$114. \int \frac{u du}{\sqrt{a + bu - cu^2}} = -\frac{\sqrt{a + bu - cu^2}}{c} \\ + \frac{b}{2c^{\frac{3}{2}}} \arcsin \left(\frac{2cu - b}{\sqrt{b^2 + 4ac}} \right) + C.$$

Other Algebraic Forms

$$115. \int \sqrt{\frac{a+u}{b+u}} du = \sqrt{(a+u)(b+u)} \\ + (a-b) \log_e(\sqrt{a+u} + \sqrt{b+u}) + C.$$

$$116. \int \sqrt{\frac{a-u}{b+u}} du = \sqrt{(a-u)(b+u)} \\ + (a+b) \arcsin \sqrt{\frac{u+b}{a+b}} + C.$$

$$117. \int \sqrt{\frac{a+u}{b-u}} du = -\sqrt{(a+u)(b-u)} - (a+b) \arcsin \sqrt{\frac{b-u}{a+b}} + C.$$

$$118. \int \sqrt{\frac{1+u}{1-u}} du = -\sqrt{1-u^2} + \arcsin u + C.$$

$$119. \int \frac{du}{\sqrt{(u-a)(b-u)}} = 2 \arcsin \sqrt{\frac{u-a}{b-a}} + C.$$

Exponential and Logarithmic Forms

$$120. \int e^{au} du = \frac{e^{au}}{a} + C.$$

$$121. \int b^{au} du = \frac{b^{au}}{a \ln b} + C.$$

$$122. \int u e^{au} du = \frac{e^{au}}{a^2} (au - 1) + C.$$

$$123. \int u^n e^{au} du = \frac{u^n e^{au}}{a} - \frac{n}{a} \int u^{n-1} e^{au} du.$$

$$124. \int u^n b^{au} du = \frac{u^n b^{au}}{a \ln b} - \frac{n}{a \ln b} \int u^{n-1} b^{au} du + C.$$

$$125. \int \frac{b^{au} du}{u^n} = -\frac{b^{au}}{(n-1)u^{n-1}} + \frac{a \ln b}{n-1} \int \frac{b^{au} du}{u^{n-1}}.$$

$$126. \int \ln u du = u \ln u - u + C.$$

$$127. \int u^n \ln u du = u^{n+1} \left[\frac{\ln u}{n+1} - \frac{1}{(n+1)^2} \right] + C.$$

$$128. \int u^m \ln^n u du = \frac{u^{m+1}}{m+1} \ln^n u - \frac{n}{m+1} \int u^m \ln^{n-1} u du.$$

$$129. \int e^{au} \ln u du = \frac{e^{au} \ln u}{a} - \frac{1}{a} \int \frac{e^{au}}{u} du.$$

$$130. \int \frac{du}{u \ln u} = \ln (\ln u) + C.$$

Trigonometric Forms

In forms involving $\tan u$, $\cot u$, $\sec u$, $\csc u$, which do not appear below, first use the relations

$$\tan u = \frac{\sin u}{\cos u}, \quad \cot u = \frac{\cos u}{\sin u}, \quad \sec u = \frac{1}{\cos u}, \quad \csc u = \frac{1}{\sin u}.$$

$$131. \int \sin u du = -\cos u + C.$$

$$132. \int \cos u du = \sin u + C.$$

$$133. \int \tan u du = -\ln |\cos u| + C = \ln |\sec u| + C.$$

$$134. \int \cot u du = \ln |\sin u| + C.$$

$$135. \int \sec u du = \int \frac{du}{\cos u} = \ln |\sec u + \tan u| + C \\ = \ln \tan \left(\frac{u}{2} + \frac{\pi}{4} \right) + C.$$

$$136. \int \csc u du = \int \frac{du}{\sin u} = \ln |\csc u - \cot u| + C \\ = \ln \tan \frac{u}{2} + C.$$

$$137. \int \sec^2 u \, du = \tan u + C.$$

$$138. \int \csc^2 u \, du = -\cot u + C.$$

$$139. \int \sec u \tan u \, du = \sec u + C.$$

$$140. \int \csc u \cot u \, du = -\csc u + C.$$

$$141. \int \sin^2 u \, du = \frac{1}{2} u - \frac{1}{4} \sin 2u + C.$$

$$142. \int \cos^2 u \, du = \frac{1}{2} u + \frac{1}{4} \sin 2u + C.$$

$$143. \int \cos^n u \sin u \, du = -\frac{\cos^{n+1} u}{n+1} + C.$$

$$144. \int \sin^n u \cos u \, du = \frac{\sin^{n+1} u}{n+1} + C.$$

$$145. \int \sin mu \sin nu \, du = -\frac{\sin(m+n)u}{2(m+n)} + \frac{\sin(m-n)u}{2(m-n)} + C.$$

$$146. \int \cos mu \cos nu \, du = \frac{\sin(m+n)u}{2(m+n)} + \frac{\sin(m-n)u}{2(m-n)} + C.$$

$$147. \int \sin mu \cos nu \, du = -\frac{\cos(m+n)u}{2(m+n)} - \frac{\cos(m-n)u}{2(m-n)} + C.$$

$$148. \int \frac{du}{1 + \cos a \cos u} = 2 \csc a \operatorname{arc} \tan (\tan \frac{1}{2} a \tan \frac{1}{2} u) + C.$$

$$149. \int \frac{du}{\cos a + \cos u} = \csc a \ln \left(\frac{1 + \tan \frac{1}{2} a \tan \frac{1}{2} u}{1 - \tan \frac{1}{2} a \tan \frac{1}{2} u} \right) + C \quad (\tan^2 \frac{1}{2} u < \cot^2 \frac{1}{2} a) \\ = 2 \csc a \tanh^{-1} (\tan \frac{1}{2} a \tan \frac{1}{2} u) + C \quad (\tan^2 \frac{1}{2} u < \cot^2 \frac{1}{2} a)$$

$$150. \int \frac{du}{1 + \cos a \sin u} = 2 \csc a \operatorname{arc} \tan (\csc a \tan \frac{1}{2} u + \cot a) + C.$$

$$151. \int \frac{du}{\cos a + \sin u} = \csc a \ln \left(\frac{\tan a - \tan \frac{1}{2} u - \sec a}{\tan a + \tan \frac{1}{2} u + \sec a} \right) + C \\ [(\cot a \tan \frac{1}{2} u + \csc a)^2 < 1] \\ = -2 \csc a \tanh^{-1} (\cot a \tan \frac{1}{2} u + \csc a) + C \\ [(\cot a \tan \frac{1}{2} u + \csc a)^2 < 1]$$

$$152. \int \frac{du}{a^2 \cos^2 u + b^2 \sin^2 u} = \frac{1}{ab} \operatorname{arc} \tan \left(\frac{b \tan u}{a} \right) + C.$$

$$153. \int e^{au} \sin nu \, du = \frac{e^{au}(a \sin nu - n \cos nu)}{a^2 + n^2} + C.$$

$$154. \int e^{au} \cos nu \, du = \frac{e^{au}(n \sin nu + a \cos nu)}{a^2 + n^2} + C.$$

$$155. \int u \sin u \, du = \sin u - u \cos u + C.$$

$$156. \int u \cos u \, du = \cos u + u \sin u + C.$$

Trigonometric Reduction Formulas

$$157. \int \sin^n u \, du = -\frac{\sin^{n-1} u \cos u}{n} + \frac{n-1}{n} \int \sin^{n-2} u \, du.$$

$$158. \int \cos^n u \, du = \frac{\cos^{n-1} u \sin u}{n} + \frac{n-1}{n} \int \cos^{n-2} u \, du.$$

$$159. \int \frac{du}{\sin^n u} = -\frac{\cos u}{(n-1)\sin^{n-1} u} + \frac{n-2}{n-1} \int \frac{du}{\sin^{n-2} u}.$$

$$160. \int \frac{du}{\cos^n u} = \frac{\sin u}{(n-1)\cos^{n-1} u} + \frac{n-2}{n-1} \int \frac{du}{\cos^{n-2} u}.$$

$$161. \int \cos^m u \sin^n u \, du = \frac{\cos^{m-1} u \sin^{n+1} u}{m+n} + \frac{m-1}{m+n} \int \cos^{m-2} u \sin^n u \, du.$$

$$162. \int \cos^m u \sin^n u \, du = -\frac{\sin^{n-1} u \cos^{m+1} u}{m+n} + \frac{n-1}{m+n} \int \cos^m u \sin^{n-2} u \, du.$$

$$163. \int \frac{du}{\cos^m u \sin^n u} = \frac{1}{(m-1)\sin^{n-1} u \cos^{m-1} u} \\ + \frac{m+n-2}{m-1} \int \frac{du}{\cos^{m-2} u \sin^n u}.$$

$$164. \int \frac{du}{\cos^m u \sin^n u} = -\frac{1}{(n-1)\sin^{n-1} u \cos^{m-1} u} \\ + \frac{m+n-2}{n-1} \int \frac{du}{\cos^m u \sin^{n-2} u}.$$

$$165. \int \frac{\cos^m u \, du}{\sin^n u} = -\frac{\cos^{m+1} u}{(n-1)\sin^{n-1} u} - \frac{m-n+2}{n-1} \int \frac{\cos^m u \, du}{\sin^{n-2} u}.$$

$$166. \int \frac{\cos^m u \, du}{\sin^n u} = \frac{\cos^{m-1} u}{(m-n)\sin^{n-1} u} + \frac{m-1}{m-n} \int \frac{\cos^{m-2} u \, du}{\sin^n u}.$$

$$167. \int \frac{\sin^n u \, du}{\cos^m u} = \frac{\sin^{n+1} u}{(m-1)\cos^{m-1} u} - \frac{n-m+2}{m-1} \int \frac{\sin^n u \, du}{\cos^{m-2} u}.$$

$$168. \int \frac{\sin^n u \, du}{\cos^m u} = -\frac{\sin^{n-1} u}{(n-m)\cos^{m-1} u} + \frac{n-1}{n-m} \int \frac{\sin^{n-2} u \, du}{\cos^m u}.$$

$$169. \int \tan^n u \, du = \frac{\tan^{n-1} u}{n-1} - \int \tan^{n-2} u \, du.$$

$$170. \int \csc^n u \, du = -\frac{\csc^{n-1} u}{n-1} - \int \csc^{n-2} u \, du.$$

$$171. \int e^{au} \cos^n u \, du = \frac{e^{au} \cos^{n-1} u (a \cos u + n \sin u)}{a^2 + n^2} \\ + \frac{n(n-1)}{a^2 + n^2} \int e^{au} \cos^{n-2} u \, du.$$

$$172. \int e^{au} \sin^n u \, du = \frac{e^{au} \sin^{n-1} u (a \sin u - n \cos u)}{a^2 + n^2} \\ + \frac{n(n-1)}{a^2 + n^2} \int e^{au} \sin^{n-2} u \, du.$$

$$173. \int u^m \cos au \, du = \frac{u^{m-1}}{a^2} (au \sin au + m \cos au) \\ - \frac{m(m-1)}{a^2} \int u^{m-2} \cos au \, du.$$

$$174. \int u^m \sin au \, du = \frac{u^{m-1}}{a^2} (m \sin au - au \cos au) \\ - \frac{m(m-1)}{a^2} \int u^{m-2} \sin au \, du.$$

Inverse Trigonometric Functions

$$175. \int \arcsin u \, du = u \arcsin u + \sqrt{1-u^2} + C.$$

$$176. \int \arccos u \, du = u \arccos u - \sqrt{1-u^2} + C.$$

$$177. \int \arctan u \, du = u \arctan u - \ln \sqrt{1+u^2} + C.$$

$$178. \int \operatorname{arctn} u \, du = u \operatorname{arctn} u + \ln \sqrt{1+u^2} + C.$$

$$179. \int \operatorname{arcsec} u \, du = u \operatorname{arcsec} u - \ln (u + \sqrt{u^2-1}) + C. \\ = u \operatorname{arcsec} u - \cosh^{-1} u + C.$$

$$180. \int \operatorname{arccsc} u \, du = u \operatorname{arccsc} u + \ln (u + \sqrt{u^2-1}) + C \\ = u \operatorname{arccsc} u + \cosh^{-1} u + C.$$

Hyperbolic Functions

$$181. \int \sinh u \, du = \cosh u + C.$$

$$182. \int \cosh u \, du = \sinh u + C.$$

$$183. \int \tanh u \, du = \ln \cosh u + C.$$

$$184. \int \operatorname{ctnh} u \, du = \ln \sinh u + C.$$

$$185. \int \operatorname{sech} u \, du = \arctan (\sinh u) + C = \operatorname{gd} u + C$$

$$186. \int \operatorname{csch} u \, du = \ln \tanh \frac{1}{2} u + C.$$

$$187. \int \operatorname{sech}^2 u \, du = \tanh u + C.$$

$$188. \int \operatorname{csch}^2 u \, du = -\operatorname{ctnh} u + C.$$

$$189. \int \operatorname{sech} u \tanh u \, du = -\operatorname{sech} u + C.$$

$$190. \int \operatorname{csch} u \operatorname{ctnh} u \, du = -\operatorname{csch} u + C.$$

$$191. \int \sinh^2 u \, du = \frac{1}{4} \sinh 2u - \frac{1}{2} u + C.$$

$$192. \int \cosh^2 u \, du = \frac{1}{4} \sinh 2u + \frac{1}{2} u + C.$$

$$193. \int \tanh^2 u \, du = u - \tanh u + C.$$

$$194. \int \operatorname{ctnh}^2 u \, du = u - \operatorname{ctnh} u + C.$$

$$195. \int u \sinh u \, du = u \cosh u - \sinh u + C.$$

$$196. \int u \cosh u \, du = u \sinh u - \cosh u + C.$$

$$197. \int \sinh^{-1} u \, du = u \sinh^{-1} u - \sqrt{1+u^2} + C.$$

$$198. \int \cosh^{-1} u \, du = u \cosh^{-1} u - \sqrt{u^2-1} + C.$$

$$199. \int \tanh^{-1} u \, du = u \tanh^{-1} u + \frac{1}{2} \ln(1-u^2) + C.$$

$$200. \int \operatorname{ctnh}^{-1} u \, du = u \operatorname{ctnh}^{-1} u + \frac{1}{2} \ln(1-u^2) + C.$$

$$201. \int \operatorname{sech}^{-1} u \, du = u \operatorname{sech}^{-1} u + \operatorname{gd}(\tanh^{-1} u) + C \\ = u \operatorname{sech}^{-1} u + \arcsin u + C.$$

$$202. \int \operatorname{csch}^{-1} u \, du = u \operatorname{csch}^{-1} u + \sinh^{-1} u + C.$$

$$203. \int \sinh mu \sinh nu \, du = \frac{\sinh(m+n)u}{2(m+n)} - \frac{\sinh(m-n)u}{2(m-n)} + C. \quad \left(m \begin{matrix} > \\ < \end{matrix} n\right)$$

$$204. \int \cosh mu \cosh nu \, du = \frac{\sinh(m+n)u}{2(m+n)} + \frac{\sinh(m-n)u}{2(m-n)} + C. \quad \left(m \begin{matrix} > \\ < \end{matrix} n\right)$$

$$205. \int \sinh mu \cosh nu \, du = \frac{\cosh(m+n)u}{2(m+n)} + \frac{\cosh(m-n)u}{2(m-n)} + C. \quad \left(m \begin{matrix} > \\ < \end{matrix} n\right)$$

$$206. \int \frac{du}{\cosh a + \cosh u} = 2 \operatorname{csch} a \tanh^{-1}(\tanh \tfrac{1}{2} u \tanh \tfrac{1}{2} a) + C.$$

$$207. \int \frac{du}{\cos a + \cosh u} = 2 \operatorname{csc} a \arctan(\tanh \tfrac{1}{2} u \tan \tfrac{1}{2} a) + C.$$

$$208. \int \frac{du}{1 + \cos a \cosh u} = 2 \operatorname{csc} a \tanh^{-1}(\tanh \tfrac{1}{2} u \tan \tfrac{1}{2} a) + C \\ (\tanh^2 \tfrac{1}{2} u < \operatorname{ctn}^2 \tfrac{1}{2} a)$$

$$209. \int e^{au} \sinh nu \, du = \frac{e^{au}(a \sinh nu - n \cosh nu)}{a^2 - n^2} + C.$$

$$210. \int e^{au} \cosh nu \, du = \frac{e^{au}(a \cosh nu - n \sinh nu)}{a^2 - n^2} + C.$$

INDEX

(The numbers refer to pages)

- Absolute convergence, 348
Acceleration, curvilinear motion, 121; rectilinear motion, 83
Adiabatic law, 70
Agnesi, witch of, 531
Anchor ring, 267
Angle of intersection, of plane curves, 43; polar form of, 126; of skew curves, 475; of surfaces, 481
Approximate formulas, 367, 372, 490
Arc, centroid of, 335; differential of, 142, 144, 473; length of, plane curve, 271; skew curve, 473
Archimedes, 127, 128, 155, 277, 534
Area, of a curved surface, 517; moment of, 320, 503, 514; moment of inertia of, 508, 514; plane, 241, 258, 498; in polar coördinates, 262, 512; of a surface of revolution, 277
Astroid, 119, 533
Auxiliary equation, 390

Bending, direction of, 75
Bernoulli, lemniscate of, 532
Binomial differentials, 299, 307
Binomial theorem, 1, 353
Boyle's law, 70

Calculation, of e , 361; of logarithms, 362; of π , 366
Cardioid, 117, 119, 125, 135, 145, 155, 244, 271, 275, 281, 323, 335, 516, 517, 533
Catenary, 152, 270, 276, 282, 423, 432, 434, 532
Cauchy, 345

Center of fluid pressure, 506
Centroid, of a homogeneous solid, 522, 526; of a plane area, 320, 337, 503; of a solid of revolution, 323
Change of variable, 166, 240, 457
Cissoid, 44, 46, 270, 277, 322, 531
Complementary function, 394
Complex number, 440
Compound-interest law, 399
Conchoid, 532
Conoid, 284
Constant, 7; absolute, 7; arbitrary, 7; of integration, 189, 229, 233, 376; numerical, 7
Continuity of functions, 12, 444
Convergence, 340
Coördinates, cylindrical, 6, 524-527; polar, 123; spherical, 6, 529, 530
Cosine curve, 533
Critical values, 52
Cubic, skew, 474
Curvature, 149; center of, 157, 171; circle of, 153, 170; radius of, 152
Curve-tracing, 81
Curvilinear motion, 120, 146
Cycloid, 116, 119, 144, 151, 161, 244, 270, 274, 276, 281, 532
Cylindrical coördinates, 6, 524-527

Derivative, definition, 21; interpretation of, by geometry, 25, 446; partial, 445; as a rate, 64; symbols for, 22, 445; total, 455; transformation of, 166
Descartes, folium of, 46, 119, 288, 533

- Differential, 136; of arc, 142, 144, 473; of area, 237; formulas for, 140; geometric interpretation, 137, 477; as an infinitesimal, 146; total, 449
 Differential coefficient, 21, 136
 Differential equations, applications to mechanics, 402; definitions, 375; first order, 378; higher order, 387; homogeneous, 380; linear, 383, 390, 407
 Differentiation, 22; formulas for, 28, 29, 86, 87, 115, 119, 420, 425, 426, 435; general rule for, 23; of implicit functions, 40, 73, 154, 458; logarithmic, 93; partial, 445, 462; successive, 73, 462
 Diocles, cissoid of, 44, 46, 270, 277, 322, 531
 Direction of a curve, 42
 Ellipsoid, 280, 285, 522
 Envelopes, 466
 Equations, graphical solution, 128; interpolation, 129; of motion, 120; Newton's method, 131
 Errors, 138, 451; percentage, 138; relative, 138
 Evolute, 158, 469; of the cycloid, 161; of the ellipse, 160, 533; of the parabola, 159, 470; properties of, 162
 Exponential curve, 89, 535
 Exponential function, 89
 Factorial number, 338
 Family of curves, 230, 466
 Fluid pressure, 325; center of, 506
 Fluxions, 19, 357
 Folium of Descartes, 46, 119, 288, 533
 Formulas, approximate, 367, 372, 490; for reference, 1-6
 Fourier, 238
 Function, complementary, 394; continuity of, 12, 444; decreasing, 50; definition of, 8, 444; derived, 21; differentiable, 21, 23; discontinuous, example of, 108; exponential, 89; of a function, 37; graph of, 10, 444; hyperbolic, 414, 415; implicit, 39, 73, 458; increasing, 50; inverse, 38; inverse hyperbolic, 423; inverse trigonometric, 105; logarithmic, 89; mean value of, 333; periodic, 97; of several variables, 444; sine, 97; table of hyperbolics, 416; transcendental, 86; trigonometric, 99
 Fundamental theorem of the integral calculus, 254-257
 Graph of a function, 10, 444
 Gravity, center of, 320, 323
 Greek alphabet, 6
 Gudermann, 435
 Gudermannian, 435; inverse, 435
 Gyration, radius of, 508
 Harmonic vibration, 403, 405
 Helix, circular, 473, 474, 482
 Horner's method, 130
 Hyperboloid, 528
 Hypocycloid, 46, 119, 156, 244, 268, 270, 276, 280, 288, 468, 533
 Increments, 19; approximation of, 137, 451
 Indeterminate forms, 174
 Inertia, moment of, 508, 514
 Infinitesimals, 17; replacement theorem, 147
 Infinity, 13
 Inflectional points, 79
 Initial conditions, 229
 Integrals, 188; change in limits, 240; decomposition of interval, 250; definite, 237; discontinuous, 251; geometric representation, 244, 492; improper, 250, 253; indefinite, 189; interchange of limits, 249; multiple, 491; table of, 538; use of table, 315

- Integrand, 195
- Integration, 187; approximate, 245;
 - of binomial differentials, 299;
 - formulas for, 191 193, 430, 432, 433, 435; fundamental theorem of, 254; by miscellaneous substitutions, 221, 305, 432; by parts, 223; by rational fractions, 289; by rationalization, 221, 296; by reciprocal substitution, 305; by reduction formulas, 307, 312; successive, 491; of trigonometric forms, 213, 303, 312
- Interpolation, 129, 372
- Interval of a variable, 7
- Involute, 163; of a circle, 156, 276, 288, 537
- Isothermal expansion, 330

- Jacobi, 445

- Laplace, 19
- Laws of the mean, 172, 182, 482
- Leibnitz, 26
- Lemniscate, 127, 155, 263, 515, 516, 517, 532
- Length of arc, plane curves, 271; in polar coordinates, 274; of skew curves, 473
- Limaçon, 534
- Limit of a variable, 10
- Limits, change in, 240; of an integral, 238; theorems on, 11, 17
- Lituus, 534
- Logarithmic curve, 89, 535
- Logarithmic differentiation, 93
- Logarithmic function, 89
- Logarithms, common, 88; natural, 87
- Loxodrome, 439

- Maclaurin's series, 357, 367
- Maxima and minima, 47; analytic treatment, 182; definitions, 52; first method, 53; functions of two variables, 483; second method, 76
- Mean value, extended theorem of, 182; of a function, 333; theorems of, 172, 482
- Mechanics, 402
- Mercator, 439; chart, 439
- Moment, of area, 320, 503; of inertia, 507, 508, 514; polar, 510, 514
- Motion, curvilinear, 120; rectilinear, 65, 83

- Napierian logarithms, 88
- Newton, 19, 27, 131, 132, 133, 332, 401
- Nicomedes, conchoid of, 532
- Normal, to a plane curve, 43; plane to a skew curve, 471, 480; to a surface, 475

- Osculating circle, 170

- Pappus, theorems of, 335, 504
- Parabola, 532, 537; cubical, 156, 531; semicubical, 266, 498, 531
- Parabolic rule, 247
- Paraboloid of revolution, 268, 521, 528
- Parameter, 115, 466
- Parametric equations, 115; first derivative, 115; second derivative, 119
- Point of inflection, 79
- Polar coordinates, 123; moment of inertia, 514; subnormal, 126; subtangent, 126
- Power rule, 32
- Pressure, fluid, 325; center of, 506
- Probability curve, 535
- Projectile, 121, 234, 471

- Quadratic equation, 1

- Radius, of curvature, 152; of gyration, 508
- Railroad curves, 152
- Rates, 64, 455

- Rectification, of plane curves, 271 ;
 in polar coordinates, 274 ; of
 skew curves, 473
 Reduction formulas, 307, 312
 Replacement theorem, 147
 Rhumb line, 439
 Rolle's theorem, 169
 Roots of equations, 128
 Rose-leaf curves, 536

 Secant curve, 535
 Sequence, 338
 Series, 338 ; absolute convergence,
 348 ; alternating, 347 ; approxi-
 mate formulas from, 367, 372 ;
 binomial, 353 ; Cauchy's test,
 345 ; comparison tests, 342 ; con-
 vergent, 340 ; differentiation and
 integration of, 365 ; divergent,
 340 ; geometric, 339 ; harmonic,
 342 ; Maclaurin's, 357 ; opera-
 tions with, 362 ; oscillating, 339 ;
 p , 344 ; power, 350, 354 ;
 Taylor's, 369, 488
 Simpson's rule, 247
 Sine curve, 533
 Skew curves, 471, 480 ; length of,
 473
 Slope of a curve, 42 ; parametric
 form, 115 ; polar form, 125
 Solids of revolution, centroid of,
 323 ; surface of, 277 ; volume of,
 265, 267, 268
 Speed, 121, 146
 Spherical coordinates, 6, 529, 530
 Spheroid, oblate, 266 ; prolate,
 266
 Spiral, of Archimedes, 127, 128, 155,
 277, 534 ; hyperbolic or recip-
 rocal, 119, 128, 264, 277, 534 ;
 logarithmic or equiangular, 127,
 128, 534 ; parabolic, 535

 Stirling, 357
 Strophoid, 534
 Subnormal, 43 ; polar, 126
 Subtangent, 43 ; polar, 126
 Successive differentiation, 73, 462
 Successive integration, 491

 Table, of hyperbolic functions, 416 ;
 of integrals, 538
 Tangent, horizontal, 42, 117 ; to a
 plane curve, 43 ; to a skew curve,
 471, 480 ; plane to a surface, 475 ;
 vertical, 42, 117
 Tangent curve, 535
 Taylor's theorem, 369, 488
 Telegraph line, 428-429
 Torus, 267
 Tractrix, 85, 270, 282, 419, 423, 436,
 537
 Transformation of derivatives, 166
 Transition curves, 152
 Trapezoidal rule, 245
 Triple integration, 521
 Trisectrix, 155, 264

 Variable, change of, 166, 457 ; defi-
 nition, 7 ; dependent, 8 ; inde-
 pendent, 8 .
 Velocity, curvilinear motion, 120,
 146 ; rectilinear motion, 65
 Vibration, damped harmonic, 405 ;
 forced harmonic, 405 ; simple
 harmonic, 403
 Volume, of a hollow solid of revo-
 lution, 267 ; of a solid with
 known cross section, 283 ; of a
 solid of revolution, 265, 267 ;
 under a surface, 501, 524 ; by
 triple integration, 521, 526

 Witch, 62, 251, 269, 322, 531
 Work, 328

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